Numerical Weather Prediction

High Resolution Modelling of the Extreme Precipitation Event over Algiers in November 2001

Forecasting Research Technical Report No. 477

Stuart Moore, Stuart Bell, Clive Wilson, Bachir Hamadache, Kamel Chikhar

email:nwp_publications@metoffice.gov.uk

© Crown copyright

Contents

1 Introduction **3**

2 The meteorological situation on the 9^{th} and 10^{th} November 2001 **5**

3 Review of previous work **12**

4 Numerical modelling and model set up **15**

5 Results **19**

5.1 Global model (60 km) runs 19

5.2 North Atlantic European (20 km) model runs 25

5.3 High Resolution Limited Area Model (4 km) runs 29

5.3.1 The effect of changing the horizontal resolution 35

5.3.2 The role of convection 35

5.3.3 The role of orography 36

5.3.4 The role of latent heat 38

6 Discussion **40**

A How the Met Office responded to the event **41**

B Project Details **43**

Abstract

In this report a study of the severe precipitation event that devastated Algiers on the night of the 9^{th} and 10^{th} November 2001 is described. Using the Met Office Unified Model, the event is simulated at global (60 km), European (20 km) and national (4 km) horizontal resolutions and analysed in detail. In doing so, the influence of model resolution on the ability to forecast such extreme precipitation events, the effects of forecast lead time, orographic and thermodynamic forcing and model parameterisation are discussed.

Results at 60 km show that it is possible to forecast a significant change in the weather and, in particular, a prolonged period of heavy (in excess of 150 mm) rainfall at least two days ahead. Increases in the horizontal resolution improve forecasts of the location, duration and intensity of the precipitation event. At a resolution of 20 km, maximum precipitation totals of 177 mm for the event are forecast. Similar totals are forecast at a resolution of 4 km. However, even at such a scale, it is found that data assimilation remains a valuable tool in accurately forecasting localised rainfall. Numerical experiments carried out using the 4 km model suggest that latent heating played a major role in the development and life cycle of the event while orographic forcing, as a means of enhancing the amount of localised precipitation, played a much smaller role.

In addition to detailing the results of the numerical simulations of the event, this report also gives an overview of other work concerning this particular event, a synoptic description of the event itself and a description of the model set up.

1 Introduction

Strong cyclogenesis events are not uncommon in the Mediterranean region but events of such intensity as the one experienced in Algiers are. Between 1800 UTC on the 9^{th} November and 1200 UTC on the 10^{th} November 2001, 260 mm of rainfall was recorded at Bouzareah. This is compared to the November average of just over 96 mm. Landslides and severe flooding of the built-up areas of Algiers, particularly the Bab-el-Oued district, resulted, leaving 776 fatalities, 126 missing and around 1500 families left without shelter.

This event is widely believed (Hamadache *et al.* (2002) for example) to be the result of a Mesoscale Convective System (MCS) which formed over the Bab-el-Oued district of Algiers. MCSs are generally defined as a precipitating system with a spatial scale of between 20-500 km and a temporal scale of up to 12 hours which, at some point during their lifetime, experience a large amount of convection. According to Zipser (1982), *"the most important point is that the MCS evolves from an early intensifying stage in which intense convection is dominant, with a strong net upward motion at low levels, through the mature stage into a decaying stage in which convective rain exists, but becomes less important, while stratiform rain associated with upward motion at high levels becomes predominant."*. Typical examples of MCSs might include large isolated thunderstorms, squall lines and sizeable convective rainbands.

Unfortunately, the heavy convective rainfall often associated with an MCS falls over only a relatively small area compared to the spatial scale of the system itself. Therefore, while it is generally possible to forecast a MCS, correctly forecasting the *intensity*, *duration* and *location* of the intense rainfall that is part of the system becomes a problem when using Numerical Weather Prediction (NWP) models with a horizontal resolution coarser than about 20 km.

According to Moore (2003), the problems experienced by mesoscale NWP models in attempting to forecast a MCS and its associated heavy convective precipitation can be attributed to,

- initialisation and quality control procedures that smooth out mesoscale features, resulting in a loss of MCS-identifying features such as narrow moist tongues, upper level jets, strong thermal gradients and vertical moisture gradients,
- a lack of initial mesoscale data to support the resolution of the model, particularly at the model boundaries,
- the non-linearity of atmospheric processes where small changes in the initial conditions can lead to large differences in the resulting forecasts,
- the accuracy of the convective parameterisation schemes used in the NWP models,
- ill-modelled boundary layer processes, and
- the inability of models to generate realistic outflow boundaries along which convection may initialise.

While this list is not exhaustive it shows clearly how everything from the initial conditions used to start the model through to the accuracy of the model physics can affect how a NWP model forecasts a MCS.

Five days prior the start of the event, forecasters at the Office National de la Météorologie (ONM) in Algiers did identify a significant change in the weather and issued a number of special weather warnings. A special forecast bulletin issued on Thursday 8^{th} November indicated an increase in precipitation affecting the coastal and central areas of northern Algeria. However, these and subsequent

shorter range forecasts at ONM failed to accurately predict the duration, intensity and location of the heaviest rainfall associated with the event.

With over $300M of damage and a large loss of life resulting from the landslides and flooding caused by the event, the Algerian government have secured a loan from the World Bank to investigate methods of reducing the vulnerability of the built-up areas of Algiers to natural disasters. With a view to making recommendations on how to upgrade the capability of ONM so that they may better deal with future events such as the one that devastated Algiers on the 9^{th}-10^{th} November 2001, this project has been conducted to investigate the meteorological evolution of the event at global, regional and country scales using the Met Office Unified Model (UM).

In section 2, an overview of the meteorological situation on the night of the 9^{th} and 10^{th} November is given using available analyses and observations. This is followed in section 3 by a literature review of previous work that has been carried out on this and similar events with regards to 1) the meteorological conditions, 2) the simulation of these events using high resolution NWP models and 3) the application of nowcasting techniques to forecast and track the evolution of these events at short lead times. The role of observing networks and flood management schemes, where they have been implemented in other flood-prone regions is also discussed briefly. Section 4 gives details about the numerical model used to carry out the numerical simulations of this event. Results from these simulations are presented in section 5. Finally, section 6 brings together the results of the numerical simulations carried out and discusses the performance of the UM in forecasting this event. Some recommendations for future work and areas of improvement for forecasting similar future events are also highlighted.

2 The meteorological situation on the 9^{th} and 10^{th} November 2001

A prevailing feature of the European meteorological situation from the 6^{th} to 10^{th} November was a low pressure system and cold front that propagated south from Scandinavia, reaching northern Algeria on the evening of Friday 9^{th} November where a strong occlusion formed with a low pressure of 996 hPa. The Met Office frontal analyses in Figure 1 clearly shows the development of this system between the 6^{th} and 11^{th} November.

Re-analyses for the same period (Figure 2) from the National Centers for Environmental Prediction (NCEP), part of the National Weather Service in the United States, depict the same situation. In these charts, a slew of cold 500 hPa air is seen approaching the Algerian coastline from northern Europe. By 0000 UTC on the 10^{th} November, this trough has reached northern Algeria and, by 0000 UTC on the 11^{th} has formed a cut-off low that coincides with the minimum in mean sea level pressure (PMSL) that is also evident on Figures 1 and 2.

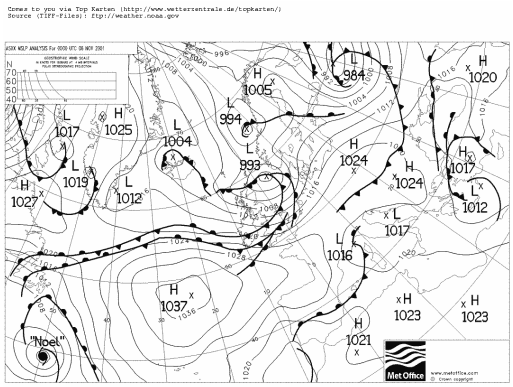
At the same time that the cold front developed over Algeria, a mass of cold air began to move eastwards towards Algeria from Morocco and dry Saharan air moved northwards towards the Algerian coastline and Balearic Islands. During the course of the 10^{th} November, these colliding air masses formed an occlusion and two low pressure centres as seen in Figure 1(e). By 0000 UTC on Sunday 11^{th} November, the occlusion was fully formed (Figure 1(f)) and the system began to move north towards the Balearic Islands which would also later experience very heavy rainfall.

The development of the weather system can also be traced using satellite imagery. Figures 3 and 4 shows infra-red imagery from Meteosat for various times during the 9^{th} and 10^{th} November. In Figure 3 the long cold front is seen moving southwards over Europe towards the Mediterranean basin. By mid-morning on the 9^{th}, the system has reached the Algerian coastline. At this stage, the images on their own give no indication of the events that will eventually occur.

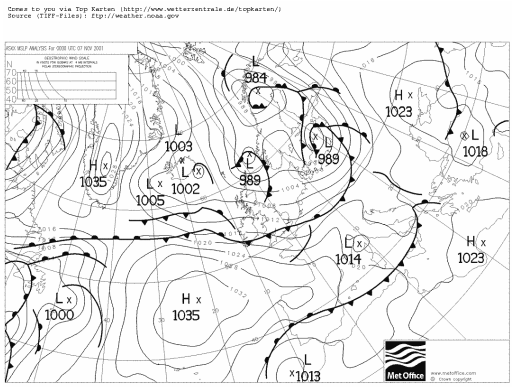
The images in Figure 4 are taken during the course of the severe precipitation event and the organisation of the cloud band represent this. In the very early hours of the 10^{th} November, the weather system has built up considerably and is sitting over the Algerian coastline and the majority of the Mediterranean Sea. By 0300 UTC (Figure 4(b)), the Meteosat image shows the development of two separate cloud bands. These are associated with the two separate regions of intense rainfall that was experienced along the Algerian coastline. This development is the result of the occluded cold front. Evidence of a dry intrusion between the two systems is also seen. Moving on to later in the morning on the 10^{th}, the cloud system is seen to remain almost stationary. There is also little change in the shape of the system. Only from approximately 0800 UTC (Figure 4(e)) does the system show any sign of weakening. Indeed, towards the end of the morning of the 10^{th}, the system does begin to move northwards, away from Algeria and towards the Balearic Islands, where it later intensified again and unleashed an enormous amount of rainfall. These images are also useful in identifying the duration of the event. From Figure 4 it appears that the most intense part of the event lasted for approximately six hours, from 0000 UTC to 0600 UTC on the morning of the 10^{th}. Rainfall data collected by ground based rain gauges confirm this.

Rainfall data is routinely collected from various sites around Algiers, and Algeria in general. Table 1 gives rainfall totals for a number of rain gauge sites located around Algiers and along the Algerian coastline for the duration of the event. For the 18-hour period 1800 UTC on the 9^{th} to 1200 UTC on the 10^{th}, Figure 5 plots totals from a selection of these sites geographically.

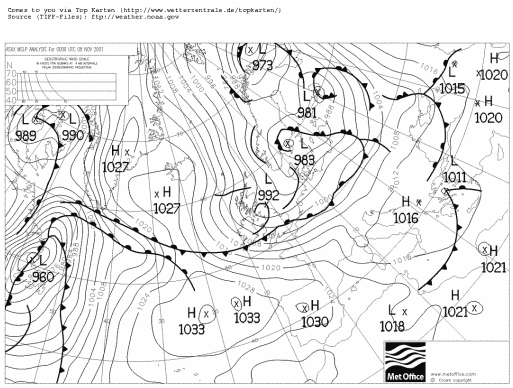
From Figure 5 an idea of the highly localised nature of the event is obtained. This is clearly seen at both Bouzareah and Cap-Tenes where local differences in the total amount of recorded precipitation, of order 260 mm and 105 mm respectively, are observed over a distances of roughly 20 km – gradients in precipitation that even very high resolution NWP models would struggle to resolve. Furthermore,



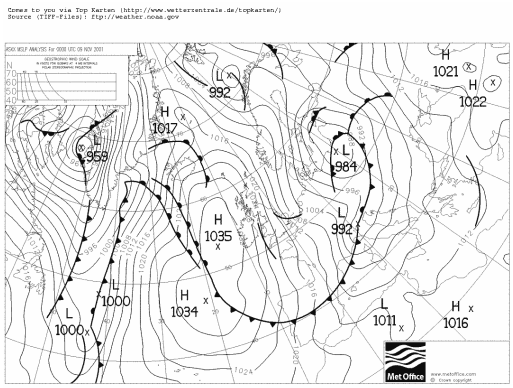
(a) 6^{th} November.



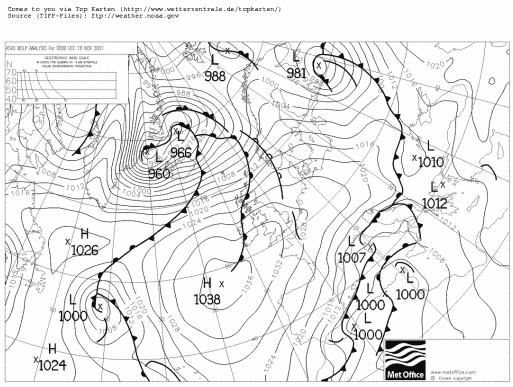
(b) 7^{th} November.



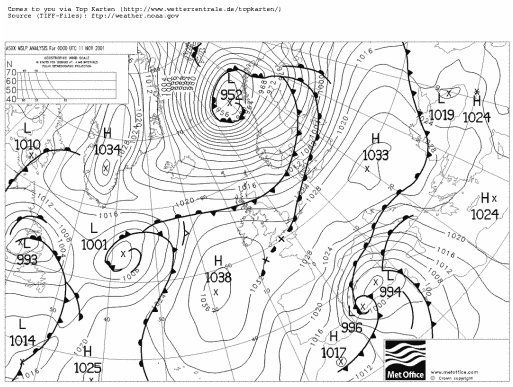
(c) 8^{th} November.



(d) 9^{th} November.

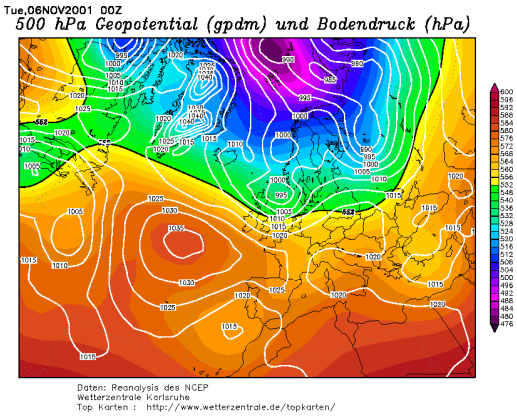


(e) 10^{th} November.

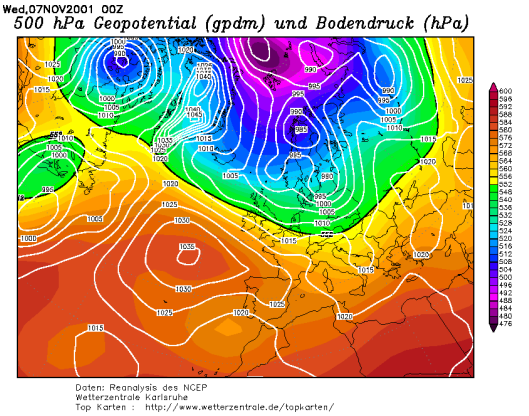


(f) 11^{th} November.

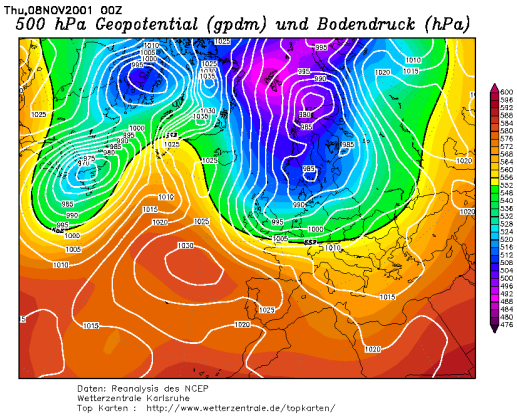
Figure 1: Plots of UKMO 0000 UTC frontal analyses and pressure at mean sea level from Tuesday 6^{th} to Sunday 11^{th} November 2001.



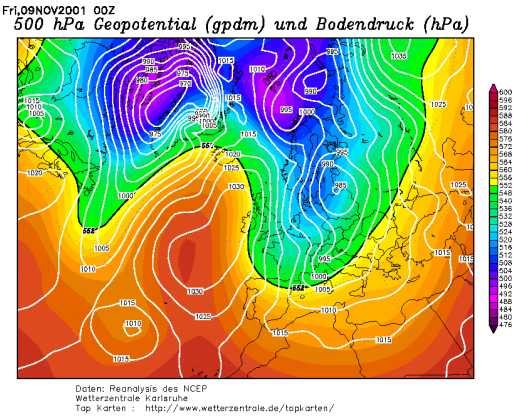
(a) 6^{th} November.



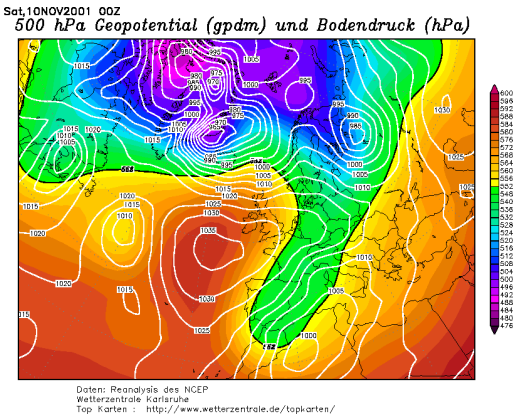
(b) 7^{th} November.



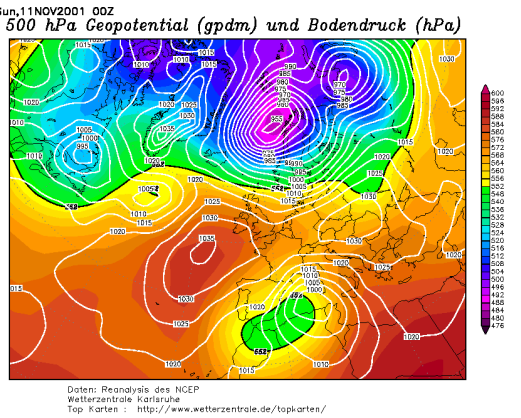
(c) 8^{th} November.



(d) 9^{th} November.

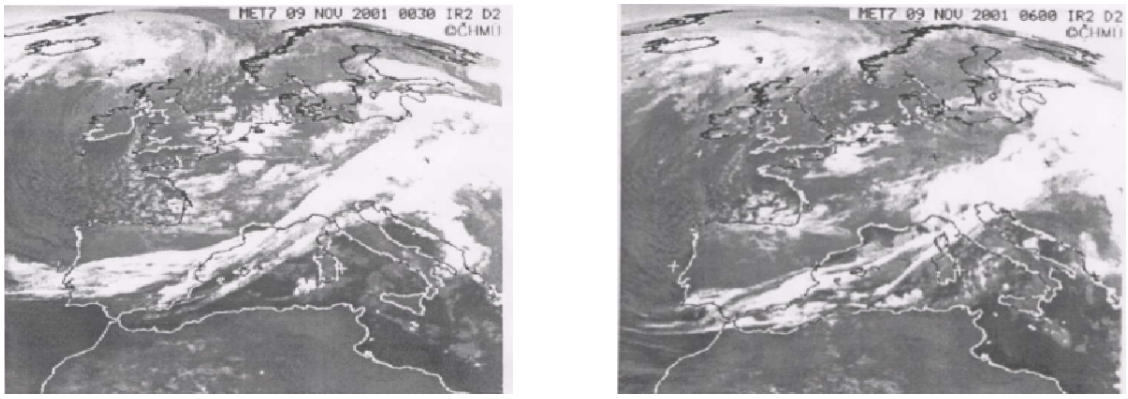


(e) 10^{th} November.



(f) 11^{th} November.

Figure 2: NCEP 0000 UTC re-analyses of 500 hPa geopotential height and surface pressure from Tuesday 6^{th} to Sunday 11^{th} November 2001.



(a) 0030 UTC.

(b) 0600 UTC.

Figure 3: Meteosat 7 infra-red imagery for early morning on the 9^{th} November 2001.

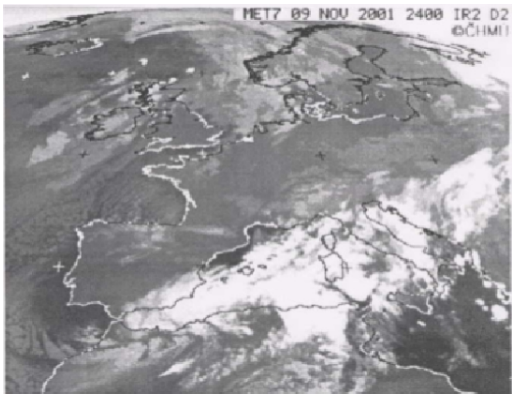
both of these locations are in the vicinity of the foothills of the Atlas mountains where there are large gradients in the local topography (Figure 8(b)) which is also likely to affect the ability of a NWP model to capture such localised details.

The rain gauge data also indicates the location of the second region of heavy rainfall to the west of Algiers. This region is located around Oran, where rainfall totals reached 92 mm in 18 hours and Beni Saf and Arzew, where totals reached 111 mm and 121 mm respectively. These locations show a close correspondence to the cloud band distribution in Figures 3 and 4. Moving from west to east, Figure 6 plots these rain gauge values for a number of the stations in Table 1 for the period 1200 UTC on the 9^{th} to 1800 UTC on the 11^{th} November, i.e. the entire weekend.

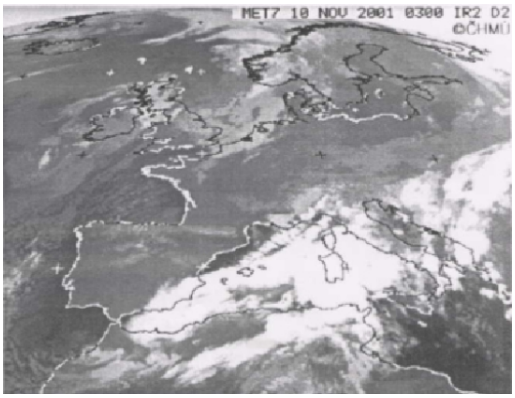
Figure 6 shows clearly the existence of two separate regions of high rainfall. Where rainfall totals in Figure 6 are larger than those for the same stations in Table 1, this is due simply to more rain falling after 1200 UTC on the 10^{th} November and is merely a product of the extended observation period used in Figure 6.

At its worst, the rain that fell at Bouzareah was in the form of violent torrential rainfall that lasted for an hour and a half, highlighting both the intensity and degree of suddenness of the event.

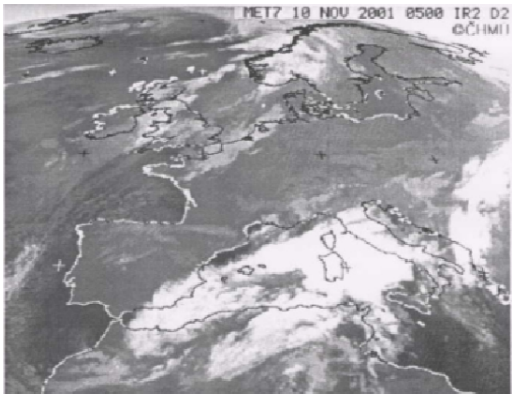
In the next section, a literature review of previous work that has been conducted on this event is presented.



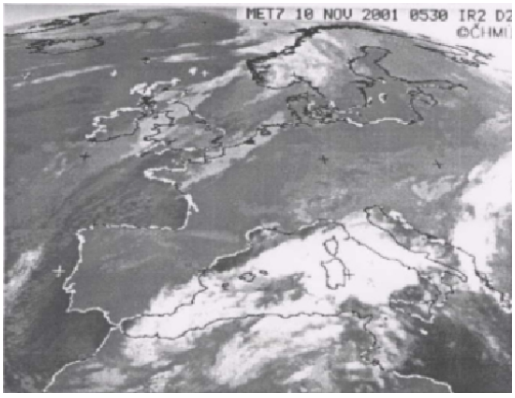
(a) 0000 UTC.



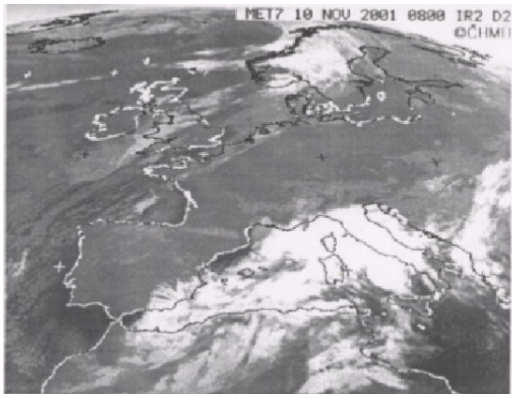
(b) 0300 UTC.



(c) 0500 UTC.



(d) 0530 UTC.



(e) 0800 UTC.

(f) 0830 UTC.

Figure 4: Meteosat 7 infra-red imagery for early to mid-morning on the 10^{th} November 2001.

Station	Location	1800 UTC 09/11 to 0600 UTC 10/11	0600 UTC 10/11 to 1200 UTC 10/11
Beni Saf	35°17'N 01°20'W	91	20
Tlemcen	34°57'N 01°16'W	55	37
Sidi Bel Abbes	35°11'N 00°37W	32	15
Oran	35°38'N 00°36'W	54	38
Tafraoui	35°29'N 00°31'W	29	45
Arzew	35°49'N 00°16'W	80	41
Mostaganem	35°53'N 00°07'W	21	38
Mascara	35°23'N 00°07'W	11	1
Saida	34°52'N 00°09'E	3	1
Cap-Tenes	36°30'N 01°20'E	45	60
Echlef	36°22'N 01°33'E	12	2
Miliana	36°18'N 02°14'E	0	0
Médéa	36°16'N 02°45'E	0	1
Bouzareah	36°48'N 03°01'E	128	132
Alger-port	36°46'N 03°06'E	72	110
Alger Dar-el-Beida	36°43'N 03°15'E	9	1
Tizi-Ouzou	36°32'N 04°03'E	2	0

Table 1: Table showing rainfall measurements (in mm) from various rain gauge site situated around Algiers and along the Algerian coastline for the period 1800 UTC on the 9^{th} November to 1200 UTC on the 10^{th} November.

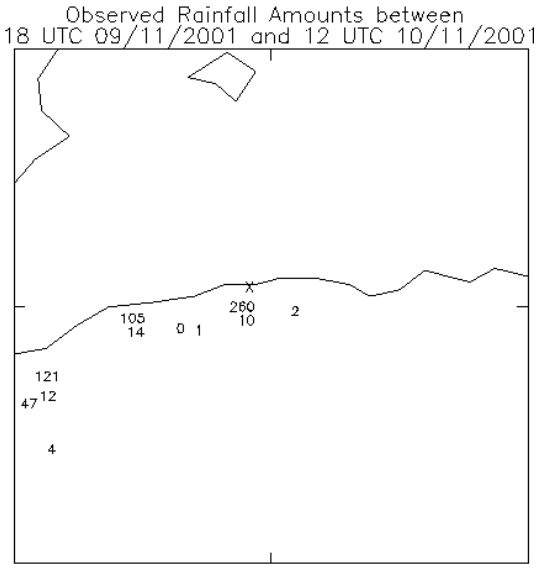


Figure 5: Rainfall map showing 18-hour accumulations of rainfall as recorded by various rain gauge sites located around Algiers. Bouzareah recored 260 mm while Cap-Tenes recorded 105 mm. Algiers is located by the "X" in the centre of the plot.

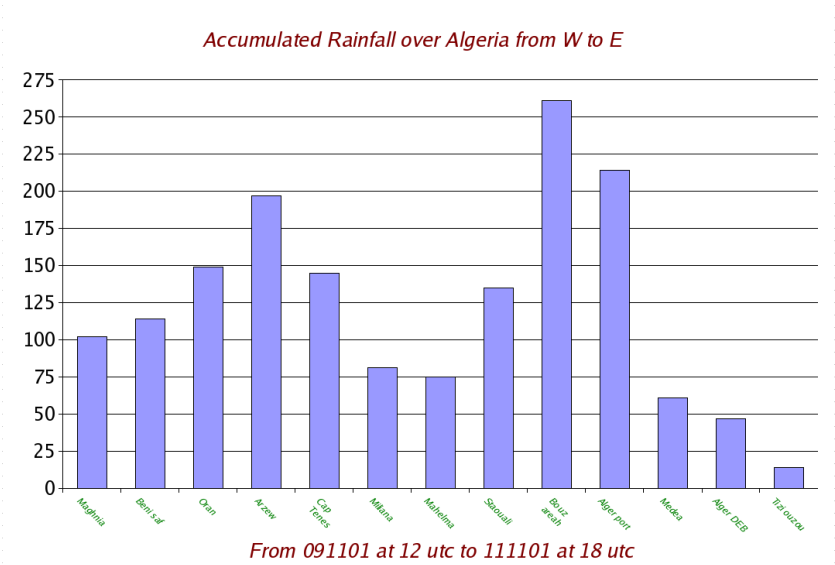


Figure 6: Bar chart showing rainfall totals measured over the course of the weekend of the 9^{th} to 11^{th} November 2001 for a number of rain gauge stations situated along the Algerian coastline. Reading from left to right, the stations are ordered from furthest west of Algiers to further east of Algiers.

3 Review of previous work

The severity of the event that hit Algiers has resulted in a number of studies directed at trying to understand the evolution of the event. Invariably, these studies have involved some form of numerical simulations. Presented here is an overview of some of the findings from this body of work. A number of studies concerning other extreme precipitation events are also considered.

A study of the event carried out by ONM (Hamadache *et al.* (2002)) was aimed at identifying the principal factors that contributed to the extreme nature of the event. ONM concluded that a strong convergence of moisture in the lowest levels of the atmosphere coupled with the presence of a potential vorticity (PV) anomaly in the upper levels of the atmosphere and a theta anomaly at low levels combined to produce a region of strong latent instability. Taking into account the likely impact of the local topography and its ability to increase the magnitude of the instability, they suggest that the precipitation that fell over the Bab-el-Oued district of Algiers was the result of a Mesoscale Convective System (MCS).

Following up with their own analysis of the contribution of diabatic (i.e moist) processes to the development of the event, Genovés and Jansà (2002) used the HIRLAM/INM NWP model to study the relative contribution of the latent heat release and surface heat fluxes throughout the initial stages of the MCS life cycle. In accordance with the findings of Hamadache *et al.* (2002), the role of the heat processes, particularly latent heat release, was found to be the most important for the development of the cyclone over Algiers. In particular, it was found that the transfer of heat between the lowest atmospheric levels and the sea surface was of prime importance. Genovés and Jansà (2002) conclude also that the complexity of the event is such that the role of PV advection and its impact on the large scale flow must be considered further.

One such study was carried out by Fierli *et al.* (2002). On the assumption that severe weather events in the extra tropics are often related to the formation of a "PV tower" throughout the troposphere, they use a contour advection transport model to track the advection of PV anomalies. Their model results, coupled with an analysis of TOMS total ozone data, showed a filamentary structure of high ozone concentration originating over Scandinavia and extending south towards the Mediterranean basin, consistent with the prevailing large scale weather conditions. Contrary to other studies, including the one presented in this report, they conclude, therefore, that the cyclone over Algiers was a polar low, rather than a MCS.

The same conclusion is reached by Tripoli *et al.* (2002). Here, a high resolution cloud resolving model is used to determine the processes that contributed to the severe precipitation event. Their results showed a number of similarities to the classic development of a polar low, namely, 1) the pre-existence of a deep trough, 2) an occluded frontal cyclone, 3) the isolation of a warm core west of the frontal zone and 4) the growth of the warm core vortex. Tripoli *et al.* (2002) comment that the primary forcing that led to the precipitation event was from PV being transported downwards from the stratosphere to the troposphere. This, combined with an injection of warm air into the region from the Sahara by the large scale flow ultimately led to the subsequent increase in intensity of the warm core vortex.

In addition to identifying the key processes involved in the development of the event, the numerical results of Tripoli *et al.* (2002) also showed that model resolutions of order 10 km and less were more than capable of capturing the overall distribution of high rainfall that was observed to the west of Algiers, as well as the distribution of low rainfall found to the east of Algiers. With a model resolution of 2.4 km, rainfall totals very close to the observed maximum were forecast but the precise location was slightly wrong. This discrepancy was attributed to the local topography around Algiers not being fully resolved by the model and it was suggested that a model resolution of several hundred meters might have lead to an improvement.

A study by Arreola *et al.* (2002) took the opportunity to investigate the extreme precipitation event over Algiers, and the deluge over the Balearic Islands on the 12^{th} November, using a hierarchy of numerical models. The models used had horizontal resolutions of 54 km, 18 km, 6 km and 2 km. As with the previously described studies, Arreola *et al.* (2002) found that the mature stage of the cyclone was heavily influenced by latent heat release which facilitated the further deepening of the cyclone. They concluded that high resolution models were of great value for predicting the rainfall potential of convective systems such as the one encountered during this event, citing the local topography, which is reasonably well resolved on horizontal scales of 2 km, as one of the key factors that contributed to the severity of the rainfall.

A recent body of work carried out at the Joint Centre for Mesoscale Meteorology (JCMM), a forecasting research branch of the Met Office, has also looked into the use of 1 km high resolution models for forecasting convective events (Roberts, 2003). On the basis that high resolution models might be better suited to modelling convective events because of the possible lack of need for a convection parameterisation scheme and better resolved local scale topography, a number of case studies were undertaken aimed at simulating events each with slightly different convective characteristics. Based on the results of these case studies, the study concluded that models of such high resolution had the potential to deliver more accurate short range forecasts of high impact precipitation events than is possible with current operational models – even when these models include a data assimilation scheme. Particularly encouraging was the ability of the 1 km model to accurately capture the triggering and location of heavy precipitation events, rather than just give a better estimate of the precipitation intensity compared to coarser resolution models. Roberts (2003) is careful to point out though that the use of such high resolution models, although potentially very useful and even more so once techniques for including high resolution observations are introduced, requires a substantial increase in computing power compared to the current operational models.

A separate study by Lean (2003), also carried out at JCMM, concluded that numerical models with a resolution higher than 12 km were able to produce more realistic structures associated with convective storm systems but that they were often in the wrong place. It was suggested this problem might be due to the high resolution model (4 km in this case) being driven by large scale forecasts from a much coarser resolution model. A final point made by Lean (2003) was that high resolution models are likely to be most useful for forecasting events with large amounts of rainfall. A recent NWP analysis of the August 2004 Boscastle flooding event in Cornwall, England by Clark *et al.* (2004) supports this, citing the 4 km model's ability to explicitly resolve the thunderstorms that led to the exceptionally high rainfall totals in the area, compared to the operationally run 12 km mesoscale models reliance on a convection scheme, as the reason for the improvement in the forecast of the event.

Previously noted by Roberts (2003), very high resolution models may be very good at forecasting intense precipitation events but there will always be a role for the assimilation of observations. Faccani *et al.* (2003) investigated this by attempting to find the best way to generate a set of initial and boundary conditions for a high resolution (3.3 km horizontal resolution) model that contained as much meteorological information over the model area as possible. Using the 1994 Piedmont flood as a case study, model runs were conducted using initial and boundary conditions from the original analysis data while the improved initial and boundary conditions included observations from upper air stations. In general, the improved initial and boundary conditions led to both positive and negative effects on the model forecasts which also showed sensitivity to both the technique by which the extra observations were assimilated and the number of extra observations that were used. Where there was an improvement in the forecast due to the use of the improved initial and boundary conditions, the biggest change occurred over land in the area most at risk of flooding.

Moving away from numerical modelling, a number of studies have also concentrated on the use of

satellites to track and study events such as the one that devastated Algiers. One such study was carried out by Pinori *et al.* (2002) who studied the events of the 9^{th} and 10^{th} November using infra-red Meteosat and Modis images and microwave measurements from the instruments on board the Defense Meteorological Satellite Program (DMSP) satellites operated by the National Oceanic and Atmospheric Administration (NOAA) in the United States. Supplementary information from ground based radars was also analysed. It was found that the satellite imagery as a whole could be used to describe the cloud properties and evolution of the convective system and was deemed by the authors as being particularly useful for describing the development of the event in areas where ground based observations were difficult to obtain. Such areas included the sea or land areas where there is no or only limited rainfall monitoring equipment. On a similar note, the Nigerian Meteorological Service have been able to make use of satellite images in their operational forecasting, where it is found to be vital to the successful forecasting of MCS events.

Combining a conceptual life-cycle model of a MCS with current nowcasting techniques and Meteosat infra-red satellite imagery, Riosalido *et al.* (1998) describe a means of tracking and forecasting the development of MCS events in the Mediterranean region. They document the results of a number of test cases and show the system to be capable of successfully identifying, tracking, diagnosing and forecasting MCSs. Once the system has identified a MCS, forecasts of its development and predicted movement are forecast and "in less than two minutes" the results are available for the forecasters to use.

Instead of being used separately, numerical models and observations, particularly from satellites can be combined to form a monitoring system and management scheme. A number of Mediterranean regions that are historically prone to severe flooding resulting from MCS events already have flood management schemes in place. Once such system used in Marseille, France is described by Deshons and Delrieu (2002). Depending on the amount of rainfall that is forecast, one of two management systems are put into practise. For light to medium rainfall events, a series of actions are carried out that aim to take advantage of the storage capability of the regions detention tanks and overflow drains, for example, and minimise the risk of exceeding the capacity of the sewer network. When heavy and severe rainfall events are expected, a management hierarchy and risk level scheme is put in place. In such cases a "public security" strategy takes precedence. Deshons and Delrieu (2002) note that the real-time application of radar imagery for nowcasting is of importance in monitoring possible flood risks.

Finally, Ferraris *et al.* (2002) document the development of an operational flood forecasting system designed for the Mediterranean environment that uses an ensemble prediction system to provide input for a locally defined hydrologic model. Ferraris *et al.* (2002) illustrate the application of this method using the 1994 Piedmont flood as a case study. They conclude that a probabilistic approach is favourable to a deterministic forecasting system when tackling the problem of flash flood forecasting and that the application of a hydrologic model is needed to better address the problems of forecasting the location of the most intense rainfall.

It appears therefore that the successful forecasting of severe precipitation, and MCS events in general, relies on the combined use of NWP models and satellite imagery, both as a source of observations for NWP model data assimilation schemes and general tracking purposes.

In the following section, the numerical model used to study the MCS event that devastated Algiers is described.

4 Numerical modelling and model set up

All of the model runs conducted in this study are performed using version 6.0 of the Met Office Unified Model (UM). The UM is unique in that the same model is used for operational forecasts, climate runs and research purposes. Furthermore, the model can, if the user desires, be coupled to an ocean or wave model. An overview of the reasons behind adopting a unified model and how the modelling system is set up is described by Cullen (1993).

Over the years there have been a number of upgrades to the model formulation. The current version of the UM, as used in this study, is built around the non-hydrostatic, semi-implicit, semi-Lagrangian "New Dynamics" core. The formulation of this new dynamical core is described by Davies *et al.* (2004).

The formulation of the model physics has also undergone numerous changes since the first version of the model. As close as possible, the model runs used here are set up to mimic closely that of the current operational set up. Briefly, this includes a mixed phase precipitation scheme (Wilson and Ballard, 1999), a mass flux convection scheme based on the scheme of Gregory and Rowntree (1990), a boundary layer turbulence scheme described by Lock *et al.* (2000) and Martin *et al.* (2000) and a two-stream radiation scheme described by Edwards and Slingo (1996).

The treatment of orography and gravity wave drag in the UM is described by Webster *et al.* (2003). It is worth noting that each of the model runs used in this study have orography fields derived from the Global Land One-kilometer Base Elevation (GLOBE) dataset (Hastings *et al.*, 1999). For each model resolution, the original 1 km data is averaged to the required model horizontal grid resolution.

Table 2 gives an overview of the basic model settings for each of the three models used in this study.

The coarse resolution model runs are performed using the 60 km global model with a full 6-hourly 3D-Var data assimilation cycle which includes all conventional and satellite observations of the time. The 3D-Var system used by the model runs in this study is described by Lorenc *et al.* (2000) and accepts measurements and observations from the following sources,

- **ATOVS**. The Advanced TIROS Operational Vertical Sounder (ATOVS) suite of instruments are on board the NOAA series of polar orbiting satellites and measure infra-red and microwave radiation across a number of frequency channels using the HIRS (infra-red) and AMSU-A and AMSU-B (microwave) instruments. Thus ATOVS is able to provide information on liquid water, ozone and surface properties, as well as information on the vertical temperature and humidity structure of the atmosphere.

- **Aircraft**. Typically these are reports collected over the course of an aircraft flight at a single level (cruise altitude). Where automatic instrumentation is fitted, reports are also possible during the ascent and descent phases of a flight. Measurements include: temperature, upper air wind speed and direction and pressure.

- **SSMI**. The Special Sensor Microwave Imager (SSMI) is on board the DMSP series of US Defense satellites and records the microwave emission from the ocean surface. With an appropriate surface emissivity model and some background information this can be used to retrieve the "surface" wind speed.

- **Satwind**. Satellite winds are derived from geostationary satellite imagery by tracking tracers (normally clouds or areas of water vapour) through successive images. The derived vector gives an indication of the wind at a specific location and height. Measurements taken include: cloud fraction, vector component wind direction and vector component wind speed,

- **Scatwind**. A Scatterometer is used to measure "surface" wind speed and direction.

- **Sonde**. Sondes are released at set observation times and take measurements throughout their ascent. Measurements taken include: temperature, upper air dew point, upper air wind speed, upper air wind direction, upper air u-component, upper air v-component, geopotential height and pressure.

- **Surface**. These are observations from a ground-based meteorological observing station taken at set times. Measurements taken include: 10 m wind speed, 10 m wind direction, visibility, 1.5 m dew point, 1.5 m relative humidity, 1.5 m temperature and the pressure at mean sea level (PMSL).

The 60 km model experiment was started on the 5^{th} November with initial conditions obtained by interpolating from a global analysis provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) which has a complete historical archive. The 60 km 3D-Var data assimilation cycle ran from the 5^{th} to the 11^{th} November with global resolution forecasts out to T+48[1] produced from each 0000 UTC and 1200 UTC analysis. These forecasts also provided the lateral boundary conditions (LBCs) that are used to drive the regional scale 20 km model.

The 20 km model used in this study is the "North Atlantic European" (NAE) model. The model domain (see Figure 7) covers Europe, much of the north Atlantic and north Africa.

Initial conditions for the 20 km model are provided by interpolation from the 60 km global analysis on the 7^{th} November. Thereafter, a 20km 3D-Var data assimilation cycle was used to provide 20 km analyses and T+36 hour forecasts were made every six hours from 0000, 0600, 1200 and 1800 UTC between the 7^{th} and 11^{th} November. The 20 km model also produced LBCs for a high resolution 4 km limited area model (LAM) that was used for the country scale modelling aspect of the project (Figure 8).

The 4 km model is driven by LBCs from the 20 km model and is initialised from a reconfigured 20 km analysis. The model is run without a data assimilation cycle out to T+36 from whatever start time is chosen. In this study, the 4 km model is used to simulate only the period around 1800 UTC on 9^{th} November and 1200 UTC on 10^{th} November, rather than capture the evolution of the low pressure system as it moved down from Scandinavia to the Mediterranean in the days prior to the event itself. Therefore, a start time of 0900 UTC on Friday 9^{th} November was chosen to allow sufficient model spin-up time and comfortably cover the entire duration of the event.

For each model run, prognostic and diagnostic output is configured to provide information at regular time intervals over the course of the model run and on a number of atmospheric levels. As such, some of the model fields that are output by the model include,

- pressure at mean sea level (PMSL),
- precipitation, including convective and large scale precipitation,
- relative humidity,
- geopotential height,
- model winds,
- sensible and latent heating fluxes, and
- potential vorticity (PV).

[1] The 60 km forecasts were restricted to T+48 as the primary function of running the global model was to provide LBCs to drive the higher resolution models and assess the impact of increasing the horizontal resolution of the model.

	Global	Regional	Hi-Res LAM
Horizontal domain			
Grid spacing	60 km	20 km	4 km
Grid size (cols × rows)	432 × 325	548 × 320	190 ×190
Vertical domain			
No. of levels	38	38	38
Boundary layer levels	13	13	13
LBCs			
Driving model	N/A	Global	NAE
LBC rim width	N/A	8	8
LBC update frequency	N/A	3 hours	1 hour
Data Assimilation			
DA Frequency	6 hours	6 hours	N/A
Model Timings			
Forecast length	T+48	T+36	T+36
Model time step	20 mins	7.5 mins	5 mins
Radiation time step	180 mins	60 mins	60 mins
Boundary layer	Richardson Number	Richardson Number	Richardson Number
Precipitation	Mixed phase	Mixed phase	Mixed phase
Convection	CAPE closure	CAPE closure	CAPE closure
CAPE closure timescale	1800 s	1800 s	1800 s
Gravity wave drag			
Gravity wave constant	1.00×10^5	1.00×10^5	3.00×10^3
Critical Froude Number	4.00	4.00	1.00
Horizontal diffusion			
Coefficient	2.5×10^5 m^2s^{-1}	-1 m^2s^{-1}	-1 m^2s^{-1}
Order of diffusion	2	0	0

Table 2: Overview of basic model set up for the three different resolutions.

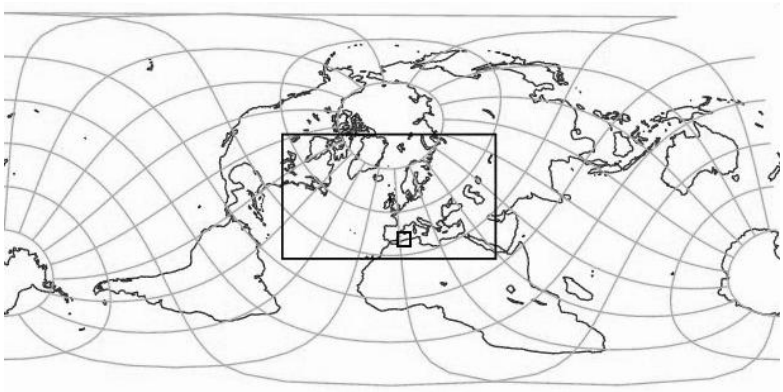
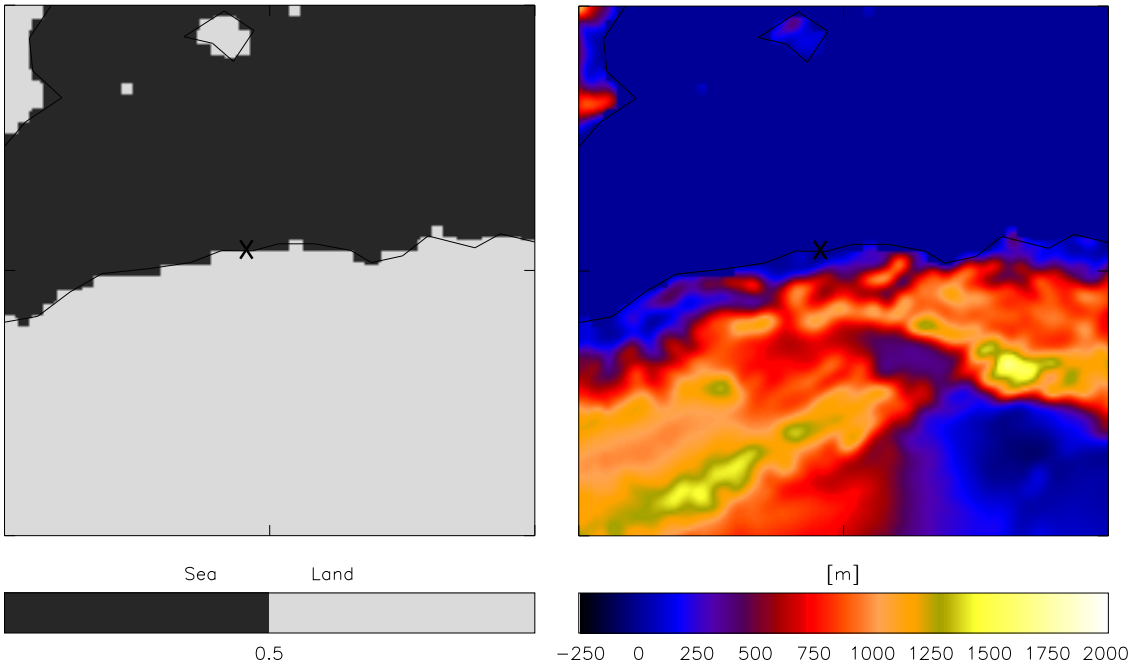


Figure 7: Schematic showing the 20 km NAE model domain nested within the 60 km global model. The high resolution 4 km model domain is shown to be nested within the 20 km domain and is centred on Algiers.



(a) 4 km model land-sea mask.

(b) 4 km model orography field.

Figure 8: Plots showing a) the 4 km model land-sea mask and b) the domain orography field. Algiers is located in the centre of the domain and indicated by an "X".

5 Results

In this section, results from runs at each of the three different model resolutions are described. In the case of the global model results in particular, the results are compared to forecasts and analyses from November 2001.

5.1 Global model (60 km) runs

The 60 km model was used to produce T+48 hour forecasts from a number of start times in the run up to the start of the event in the evening of the 9^{th} November. Results from two forecasts are presented here, although it should be noted that similar results were obtained from the other forecasts.

Looking first at the model precipitation forecasts, Figure 9 shows 12-hour accumulations of the total precipitation field from two separate forecasts. One forecast is started at 1200 UTC on the 8^{th} November and the second is started at 0000 UTC on the 9^{th} November. The total precipitation comprises of the large scale snow and rainfall amounts as well as the convective scale snow and rainfall amounts.

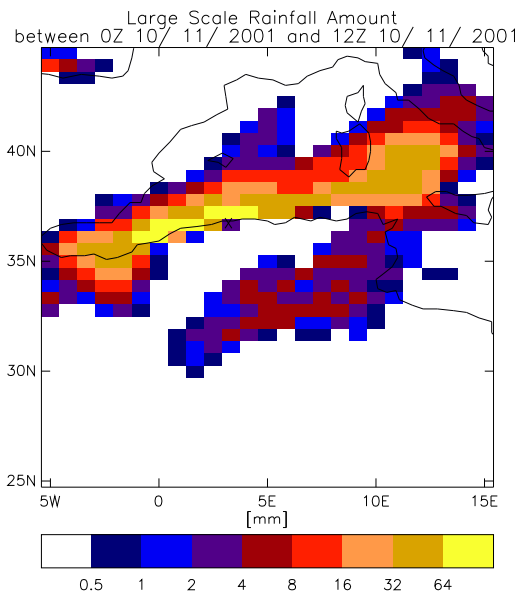
A high amount of precipitation is forecast from each model run, with maximum values of at least 50 mm forecast for each 12-hour period. However, both model forecasts have the maximum precipitation located to the northwest of Algiers and over the Mediterranean Sea. That aside, summing the total precipitation amount over the 36-hour period covered by Figures 9(b), 9(c) and 9(d) yields an accumulation in excess of 150 mm. While this is lower than the peak amount measured during the event (260 mm at Bouzareah), this forecast and the one issued 12 hours earlier (Figure 9(a)) clearly indicate a prolonged period of heavy rainfall is to be expected over northern Algeria. It should be noted that an underestimation of this magnitude would be expected of a coarse resolution global model. Both forecasts show the period of greatest rainfall to be between 0000 UTC and 1200 UTC on the 10^{th} November. The large accumulation forecast for the period 1200 UTC on the 10^{th} to 0000 UTC on the 11^{th} November may well be linked to the low pressure system that remains over northern Algeria and the Balearic Islands over the course of the 10^{th} November, as analysed in Figure 1(f).

Neglecting the snowfall components of the total precipitation field, it is possible to look at the large scale and convective scale precipitation fields separately. Figure 10 shows 12-hour accumulations of the large scale precipitation for the same model forecasts and times as shown in Figure 9.

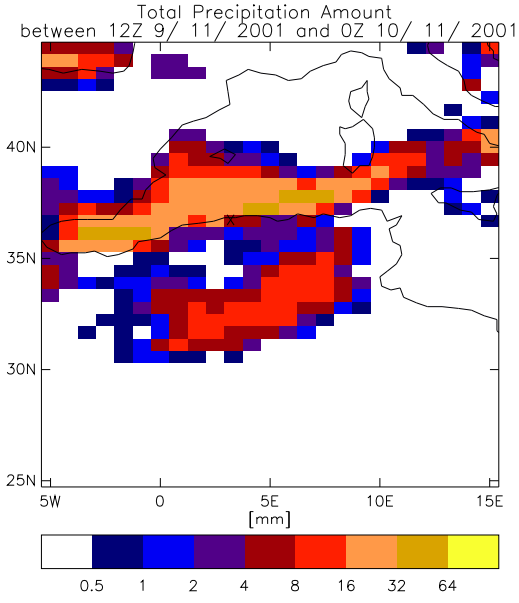
It is clear, by directly comparing the plots in Figure 10 with those in Figure 9, that the large scale precipitation contributes only a small amount of the total precipitation field. In general, the large scale precipitation contributes only as much as 16 mm and up to 32 mm in isolated regions. Looking at the distribution of the rain band, the large scale precipitation is located primarily over the Mediterranean Sea and contributes little to any rainfall that fell over Algiers. Looking further afield, it is noted that the large scale precipitation makes no contribution at all the the precipitation event that occurred over northern Spain at the same time.

In stark contrast, the convective scale precipitation makes up the vast majority of the rainfall that fell during the event. Figure 11 shows 12-hour accumulations of the convective scale rainfall for the same periods as used in Figures 9 and 10.

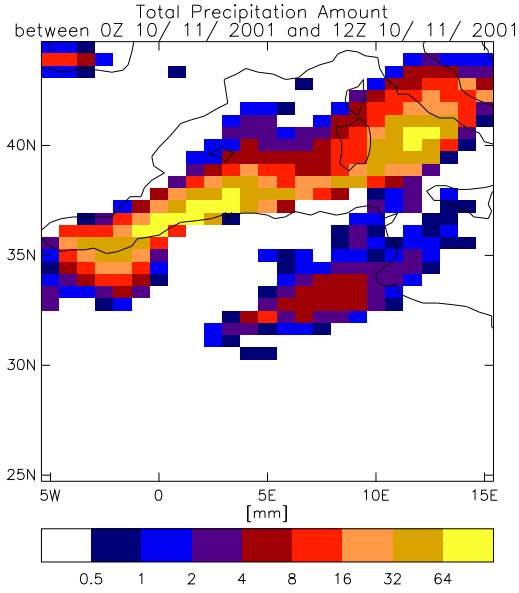
The convective scale is regarded as any horizontal scale less than the grid scale. Thus for the global model, this is any distance less than 60 km. The region of maximum convective precipitation is located along the Algerian coastline, as opposed to over the sea as is the case with the large scale rainfall, with accumulations in excess of 64 mm in some places. A large accumulation of convective scale rain is even predicted by the earliest of the forecasts studied here (Figure 11(a)), suggesting



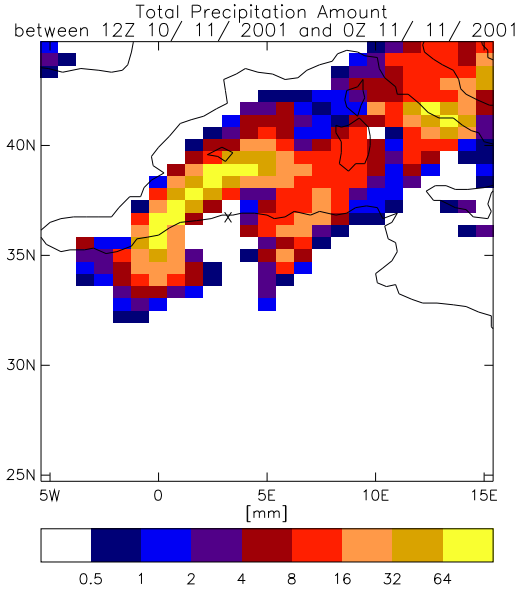
(a) T+36 to T+48 from 1200 UTC on 8/11.



(b) T+12 to T+24 from 0000 UTC on 9/11.

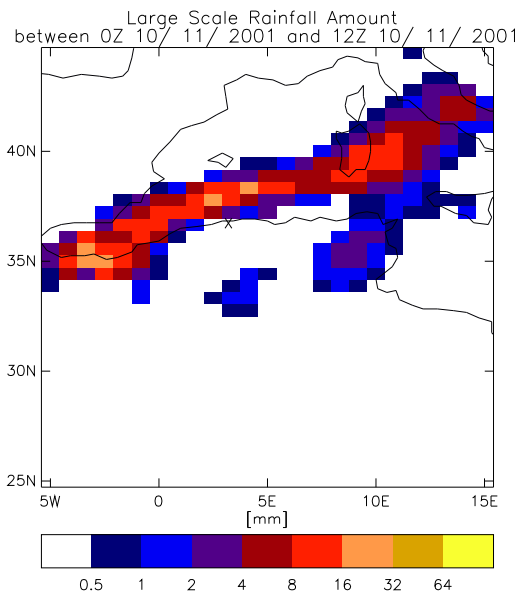


(c) T+24 to T+36 from 0000 UTC on 9/11.

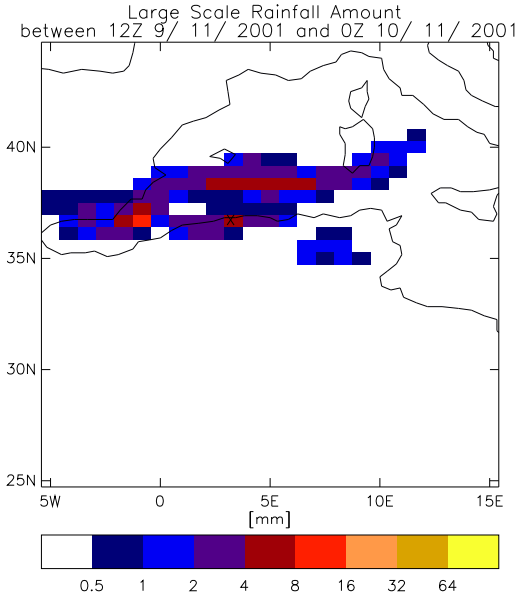


(d) T+36 to T+48 from 0000 UTC on 9/11.

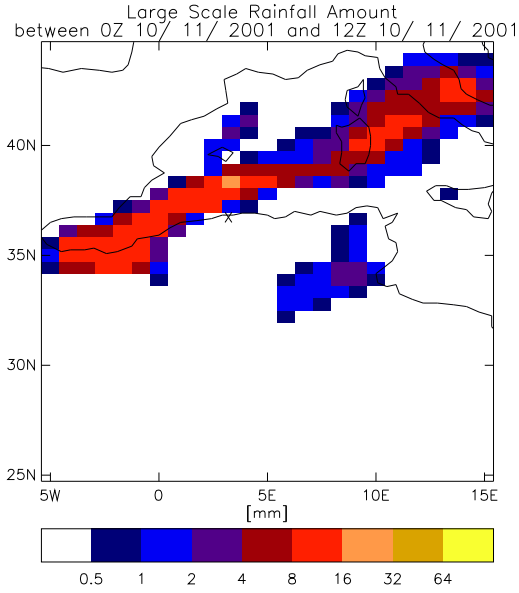
Figure 9: 12-hour accumulations of the total precipitation amount from a) a 60 km forecast started at 1200 UTC on the 8^{th} November and b), c) and d) a 60 km forecast started at 0000 UTC on the 9^{th} November. Panels a) and c) can be directly compared to each other.



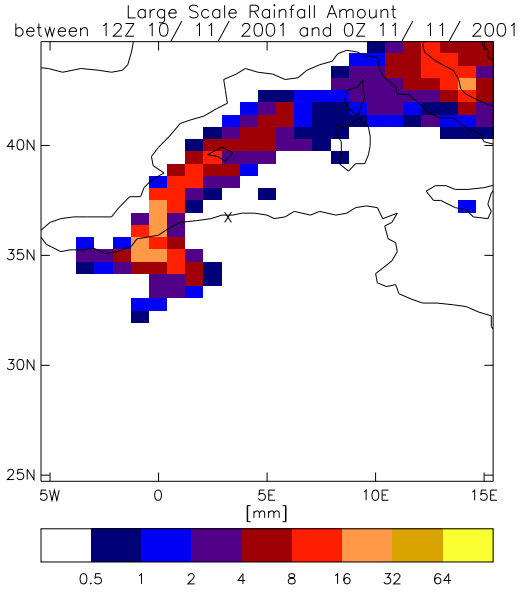
(a) T+36 to T+48 from 1200 UTC on 8/11.



(b) T+12 to T+24 from 0000 UTC on 9/11.

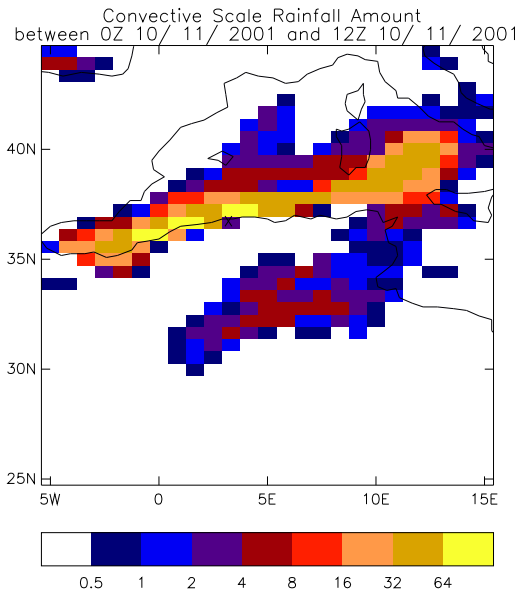


(c) T+24 to T+36 from 0000 UTC on 9/11.

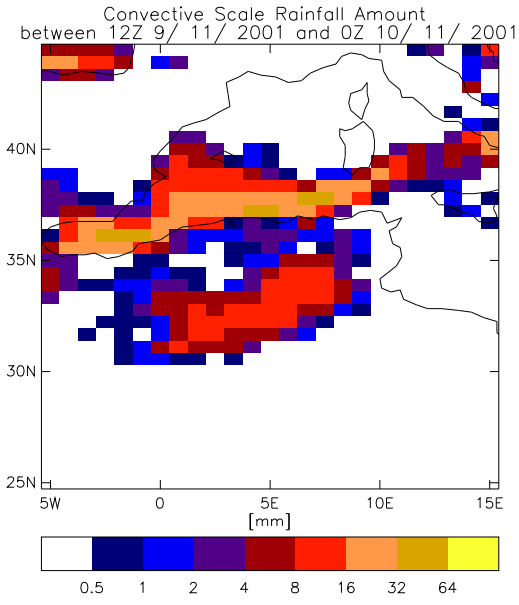


(d) T+36 to T+48 from 0000 UTC on 9/11.

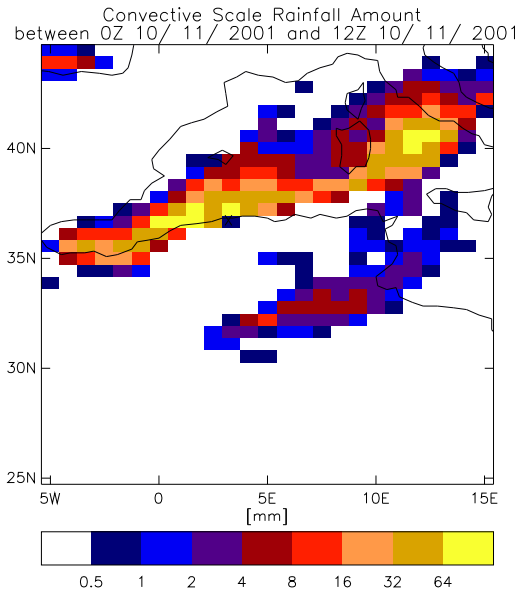
Figure 10: 12-hour accumulations of the large scale precipitation amount from a) a 60 km forecast started at 1200 UTC on the 8^{th} November and b), c) and d) a 60 km forecast started at 0000 UTC on the 9^{th} November. Panels a) and c) can be directly compared to each other.



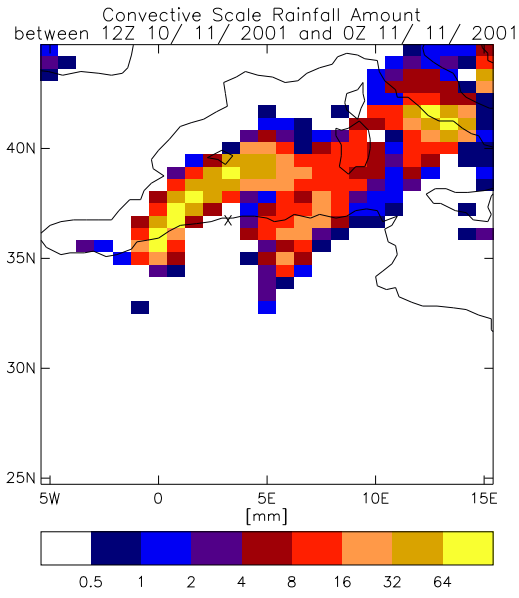
(a) T+36 to T+48 from 1200 UTC on 8/11.



(b) T+12 to T+24 from 0000 UTC on 9/11.



(c) T+24 to T+36 from 0000 UTC on 9/11.



(d) T+36 to T+48 from 0000 UTC on 9/11.

Figure 11: 12-hour accumulations of the convective scale precipitation amount from a) a 60 km forecast started at 1200 UTC on the 8^{th} November and b), c) and d) a 60 km forecast started at 0000 UTC on the 9^{th} November. Panels a) and c) can be directly compared to each other.

some degree of predictability of the event and some skill of the model itself.

These results are in accordance with the findings of a number of earlier studies on the event (see section 3) which suggest the event was a Mesoscale Convective System. In a MCS, the total precipitation is dominated by rainfall on the convective scale.

Concentrating now only on results from the model forecasts started at 0000 UTC on the 9^{th} November, Figure 12 presents forecasts of the PMSL from T+24 to T+48.

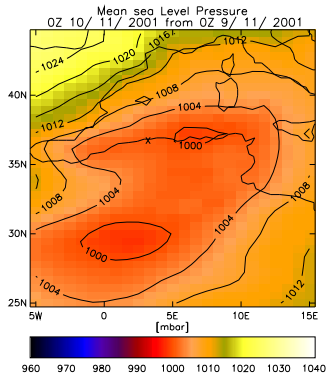
This sequence of forecasts agrees very well with the Met Office analyses at 0000 UTC on both the 10^{th} and 11^{th} November and a pressure of around 1000 hPa for the region around Algiers is predicted. Regions of lower atmospheric pressure are initially located to the south of Algiers (Figure 12(a)) and are forecast to move northwards towards the Balearic Islands (Figure 12(c). This is the same situation as depicted in the Met Office analyses charts (Figure 1).

A similarly good agreement between model forecasts and NCEP re-analyses is found for the 500 hPa geopotential height field. Figure 13 shows forecasts of the 500 hPa geopotential height field for 0000 UTC on the 10^{th} November and 0000 UTC on the 11^{th} November.

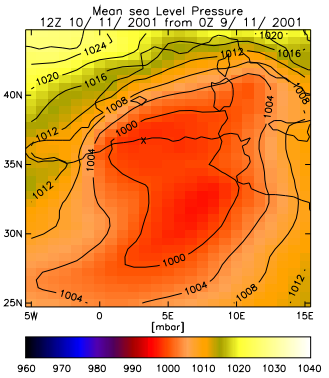
Figure 13(a) shows a tongue of low (and cold) 500 hPa air to be located over eastern Spain and northwestern Algeria at 0000 UTC on the 10^{th} November. Twenty four hours later, the model is forecasting a cut-off low in the 500 hPa geopotential height field situated directly over Algiers. With a minimum value of 540 dm (5400 m), the 60 km has made a good job of forecasting the 500 hPa geopotential height field and this is verified by comparing both plots in Figure 13 with the corresponding analyses presented in Figure 2.

Forecasts made by the 60 km model but started at various other times all predict the same evolution of the main model fields presented here. This not only hints at some degree of predictability in the event on large scales, but suggests a reasonable amount of confidence can be placed on the model and its use of observations to forecast such an event on a global scale.

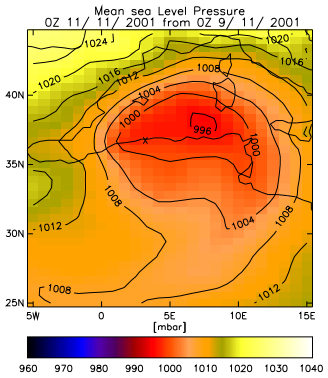
In the next section, the performance of the 20 km regional scale model is assessed.



(a) T+24 from 0000 UTC on 9/11.

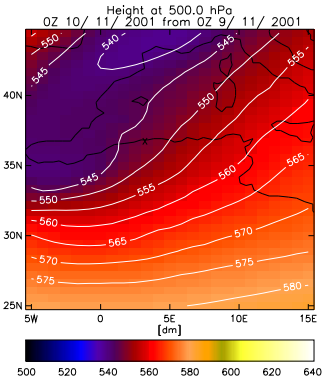


(b) T+36 from 0000 UTC on 9/11.

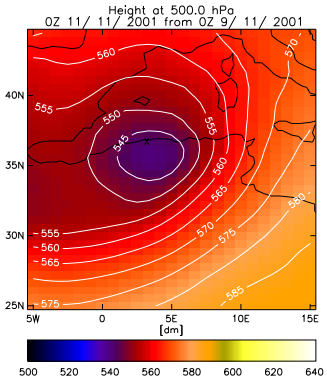


(c) T+48 from 0000 UTC on 9/11.

Figure 12: Forecasts of PMSL for a) 0000 UTC on the 10^{th} November, b) 1200 UTC on the 10^{th} November and c) 0000 UTC on the 11^{th} November. The forecast was started at 0000 UTC on the 9^{th} November.



(a) T+24 from 0000 UTC on 9/11.



(b) T+48 from 0000 UTC on 9/11.

Figure 13: Forecasts of 500 hPa geopotential height for a) 0000 UTC on the 10^{th} November and b) 0000 UTC on the 11^{th} November. The forecast was started at 0000 UTC on the 9^{th} November.

5.2 North Atlantic European (20 km) model runs

The set up for the 20 km model is very similar to that of the 60 km model, the main differences being shorter (T+36) forecasts and forecasts started every six hours instead of twelve. Differences between the model physics and timings are reported in Table 2.

Figure 14 shows 6-hour accumulations of the total precipitation field as predicted by three different forecasts from the 20 km model.

Each of the three forecasts predict a large amount of precipitation to fall along the Algerian coastline and, between themselves, agree very well on both the location of the main rain band and the timing of the most intense periods of the rainfall. This is generally between 0000 UTC and 0600 UTC on the morning of the 10^{th} November where 6-hour accumulations greater than 64 mm are predicted. In general, accumulations for the same 6-hour periods increase as the forecast lead time is shortened.

As with the 60 km model forecasts, the 20 km model has successfully captured the severe precipitation well and highlighted the onset, duration and decay periods of the event. Each of the three forecasts predict a similar, if not slightly greater amount of precipitation over the Algiers region than was previously forecast by the 60 km model. The forecast started at 0000 UTC on the 9^{th} November has, for the 18-hour period 1800 UTC on the 9^{th} to 1200 UTC on the 10^{th}, a maximum accumulation of 177 mm falling just to the west of Algiers. This particular region of high rainfall may be associated with the occlusion that occurred over northwestern Algeria producing the high rainfall totals over Arzew and Oran. Thus, this may be the result of the model combining the two regions of rainfall instead of allowing them to develop separately as the rain gauge data suggests they did.

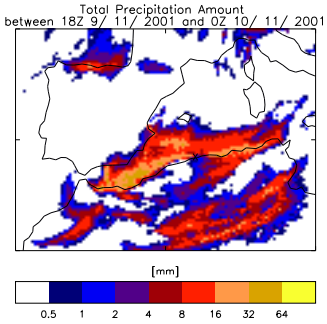
Splitting the total precipitation field into its large scale and convective scale components we again see that, even with a horizontal resolution of 20 km, the vast majority of the rainfall is on the convective scale. Figure 15 compares the large scale and convective scale rainfall accumulations for three consecutive 6-hour periods from a forecast started at 0000 UTC on the 9^{th} November. Accumulations for the same time periods from other 20 km forecasts predicted similar magnitudes and distributions of the rainfall.

The large scale rainfall (Figures 15(a), 15(b) and 15(c)) is clearly much less than the convective component and, compared to Figures 15(d), 15(e) and 15(f), it is seen that the large scale component of the total precipitation fell more consistently than the convective component. This is borne out by the fact that there is no large increase in the 6-hour accumulation maximums. There is, however, some indication as to the development of the large scale rainfall with the rain band spreading out along the Algerian coastline in the hours up to 0600 UTC on the morning of the 10^{th} November, followed by a northwards movement of the rain band in the following six hours.

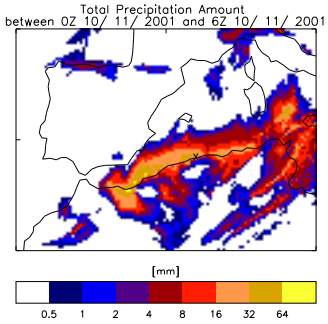
The convective scale rainfall is more widespread than its large scale counterpart. In addition to the main rainfall band stretching out along the Algerian coastline, we find that a high proportion of the rain that is predicted to fall inland is forced on the convective scale. As was noted in the 60 km model forecasts, the heavy rainfall forecast for northern Spain is again confirmed be to solely convective. Of the maximum 177 mm of precipitation forecast by the 20 km model, the convective scale rainfall contributes in excess of 100 mm of the total in the region of maximum precipitation just to the west of Algiers over the eighteen hours that the event lasted.

Concentrating solely on the 20 km forecast started at 0000 UTC on the 9^{th} November, Figure 16 shows the PMSL field at three different forecast times during the event.

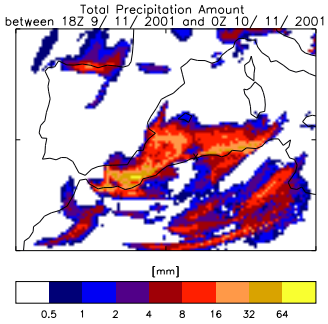
Figure 16 shows the progressive deepening of the low pressure centre over Algiers over the course of the morning of the 10^{th} November, reaching 996 hPa. This is a deeper low pressure centre and is better positioned, compared to available analyses, than was obtained using the 60 km model.



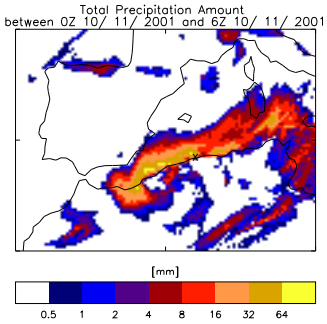
(a) T+24 to T+30 from 1800 UTC on 8/11.



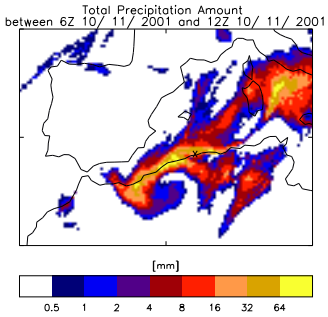
(b) T+30 to T+36 from 1800 UTC on 8/11.



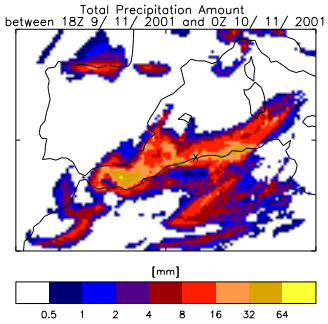
(c) T+18 to T+24 from 0000 UTC on 9/11.



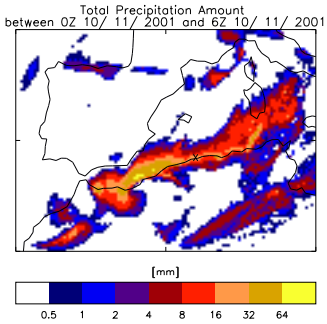
(d) T+24 to T+30 from 0000 UTC on 9/11.



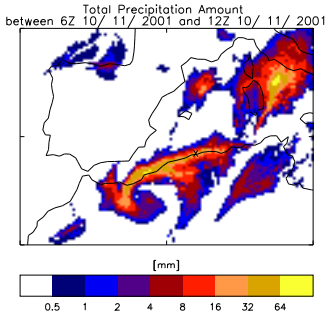
(e) T+30 to T+36 from 0000 UTC on 9/11.



(f) T+6 to T+12 from 1200 UTC on 9/11.

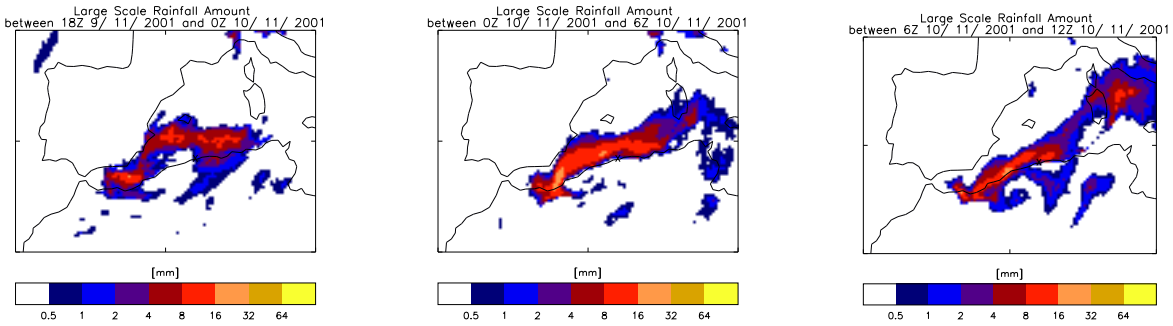


(g) T+12 to T+18 from 1200 UTC on 9/11.



(h) T+18 to T+24 from 1200 UTC on 9/11.

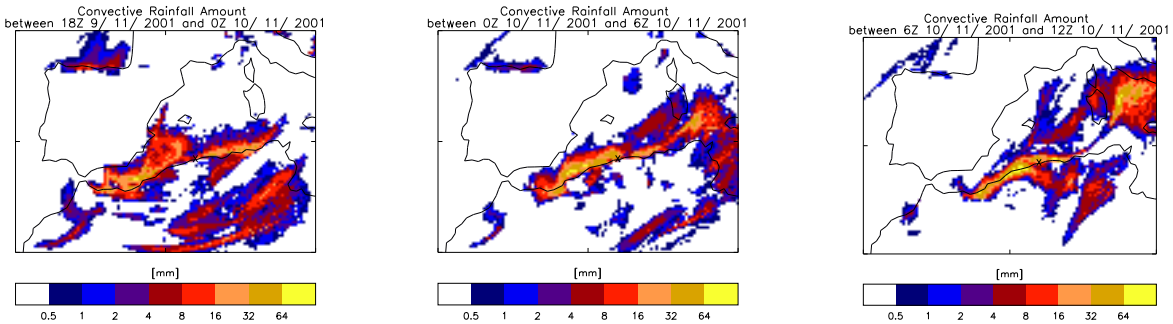
Figure 14: 6-hour accumulations of the total precipitation field from three different forecasts with the 20 km model. Panels a) and b) are from a forecast started at 1800 UTC on Thursday 8^{th} November, panels c), d), e) and f) are from a forecast started at 0000 UTC on the 9^{th} and panels f), g) and h) are from a forecast initiated at 1200 UTC on the 9^{th} November.



(a) T+18 to T+24 from 0000 UTC on 9/11.

(b) T+24 to T+30 from 0000 UTC on 9/11.

(c) T+30 to T+36 from 0000 UTC on 9/11.

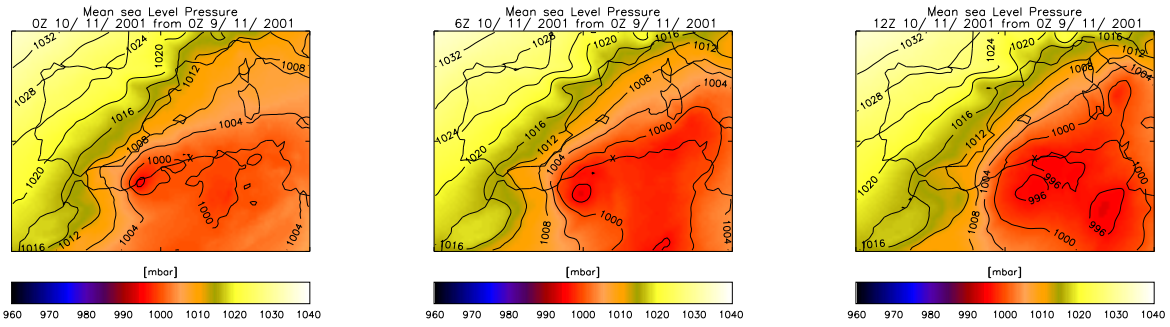


(d) T+18 to T+24 from 0000 UTC on 9/11.

(e) T+24 to T+30 from 0000 UTC on 9/11.

(f) T+30 to T+36 from 0000 UTC on 9/11.

Figure 15: 6-hour accumulations of the large scale and convective scale precipitation fields from a 20 km forecast started at 0000 UTC on the 9^{th} November. Panels a) and b) and c) show the large scale component of rainfall while panels d), e) and f) show accumulations of the convective scale rainfall.



(a) T+24 from 0000 UTC on 9/11.

(b) T+30 from 0000 UTC on 9/11.

(c) T+36 from 0000 UTC on 9/11.

Figure 16: Forecasts of PMSL for a) 0000 UTC on the 10^{th} November, b) 0600 UTC on the 10^{th} November and c) 1200 UTC on the 10^{th} November. The forecast was started at 0000 UTC on the 9^{th} November.

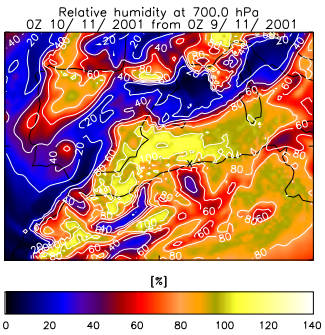
In general, this particular forecast, and the other 20 km forecasts that were run, agree well with each other and the analyses. Indeed, the T+36 forecast for 1200 UTC on the 10^{th} November (Figure 16(c)) highlights three separate regions where the PMSL is 996 hPa. This is clearly a benefit of the increase in resolution compared to the 60 km model fields, although it is equally likely in this particular situation that having three low pressure centres extremely close to each other is the result of the contouring algorithm used to plot the PMSL field.

In line with the improvement in the PMSL field compared to the 60 km model forecasts, the 500 hPa geopotential height field (not shown) also showed signs of improvements in terms of both the general position of the tongue of 500 hPa air in the early stages of the event and later on with respect to the magnitude and location of the cut-off which began to develop from 0600 UTC on the 10^{th}. An important result that use of a 20 km model has brought about is the improvement in the model's ability to forecast the formation of the dry intrusion that separated the two rainfall systems. These systems are the occluded front over Oran and Arzew to the west of Algiers and the MCS that formed over Algiers itself. Figure 17 shows forecasts of the 700 hPa relative humidity field from a start time of 0000 UTC on the 9^{th} November.

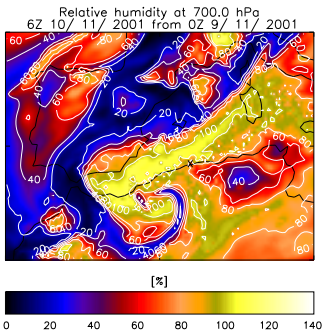
The 700 hPa relative humidity field is regularly used by forecasters as a proxy for the most likely location of any rainfall. It does not, however, give any indication as to the amount of rainfall that might be expected. Throughout the duration of the forecast shown in Figure 17, there is a band of high relative humidity (in excess of 100%) located along the Algerian coastline, roughly coincident with the location of the large scale rainfall band. Relative humidity values greater than 100% are possible since the model's microphysics scheme allows ice-supersaturation.

Not only does this field tell us about the large region of saturated air over Algiers but it also shows the development of the dry intrusion that was previously observed in the satellite imagery (Figure 4). In Figure 17, the dry intrusion is evidenced by a region of dry (approximately 30% saturation only) air wrapping itself around the occlusion in an anticlockwise direction over Oran and Arzew to the west of Algiers.

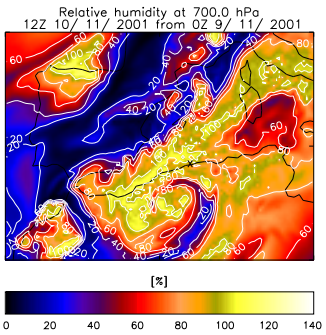
In summary, the 20 km model has led to an overall improvement in the model forecasts compared to those made with the 60 km model. This is in terms of the both the position and magnitude of a number of large scale features associated with the event. There has been an increase in the maximum precipitation accumulation for the duration of the event from 150 mm to 177 mm but the location



(a) T+24 from 0000 UTC on 9/11.



(b) T+30 from 0000 UTC on 9/11.



(c) T+36 from 0000 UTC on 9/11.

Figure 17: Forecasts of the 700 hPa relative humidity field for a) 0000 UTC on the 10^{th} November, b) 0600 UTC on the 10^{th} November and c) 1200 UTC on the 10^{th} November. The forecast was started at 0000 UTC on the 9^{th} November.

of this maximum has remained to the west of Algiers. The increase in horizontal resolution has also led to an improvement in the forecasting of other meteorological systems related to the event, the most notable being the improved forecasts of the dry intrusion between the occlusion and MCS.

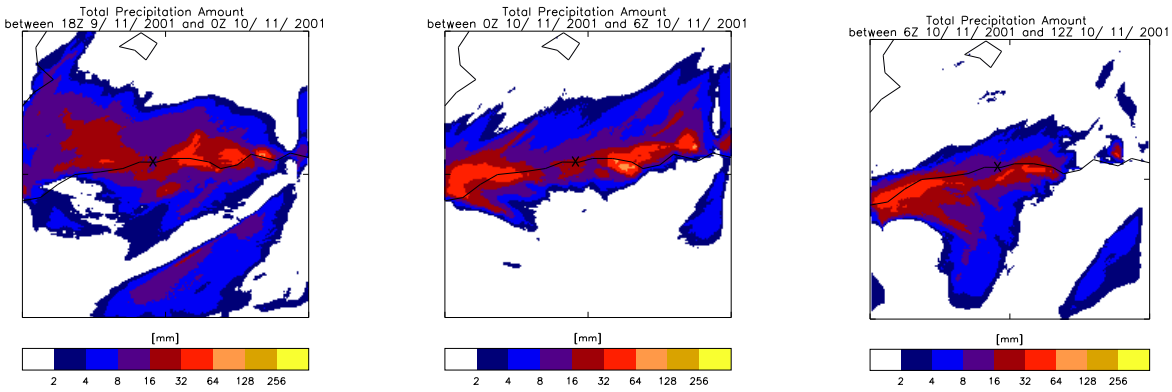
In the next section, results from model runs where the horizontal resolution is increased further to 4 km are presented. At this resolution, a number of numerical experiments that looked specifically at the role of convection, orography and latent heating in the event were conducted. Results from these runs are presented.

5.3 High Resolution Limited Area Model (4 km) runs

Forecasts made with the 4km LAM are aimed at identifying some of the more localised structures associated with the severe precipitation event than is possible with either the 60 km or 20 km models. Running the model at such a resolution is geared towards achieving two benefits. The first relates to the possibility of explicitly resolving convection on the grid scale thereby avoiding any problems due to inadequacies in the convective parameterisation scheme employed in the model. The second focuses on improvements to the orographic forcing of precipitation as the local orography is much better resolved at the 4 km scale. Both of these situations are described in more detail in sections 5.3.2 and 5.3.3 respectively. As a result it is believed, but not guaranteed, that an increase to a horizontal resolution of 4 km will lead to an increase in the precipitation accumulation totals, which have so far failed to reach the event maximum of 260 mm.

6-hour accumulations of the total precipitation field for a forecast started at 0900 UTC on the 9^{th} November are shown in Figure 18.

The 4 km model shows, much more so than was seen in the 60 km and 20 km models, that the most intense period of the event with regards to the rainfall was during the first six hours of the morning of the 10^{th} November. Figure 18(b) has a maximum accumulation of 95 mm located just to the east of Algiers. This is also different to the 60 km and 20 km models which had previously positioned the region of most intense rainfall predominately to the west of Algiers. Of note here also is the clear separation between the two areas of high rainfall. This situation was observed in the satellite imagery and hinted at by the rain gauge data but had not been well depicted by forecasts from either



(a) T+9 to T+15 from 0900 UTC on 9/11.

(b) T+15 to T+21 from 0900 UTC on 9/11.

(c) T+21 to T+27 from 0900 UTC on 9/11.

Figure 18: 6-hour accumulations of the total precipitation field from a 4 km model forecast started at 0900 UTC on Friday 9^{th} November. Please note the change in scale from previous plots.

the 60 km or 20 km models. Summing the accumulations for the whole eighteen hour duration of the event gives a maximum, local accumulation of 165 mm which is located just to the east of Algiers.

Figure 18(c) also indicates a much weaker precipitation field than is the case in the earlier hours of the event. This is indicated not only by a small maximum accumulation (just 56 mm located in the region of high rainfall over Arzew and Oran) but in the spread of the model precipitation field. For the period 0600 UTC to 1200 UTC on the 10^{th} November, the distribution of rainfall is visibly less than at earlier stages during the event and suggests that the most intense part of the event has passed. Infra-red satellite imagery for late in the morning of the 10^{th} (Figures 4(e) and 4(f)) support this, showing a change in contrast in the cloud system from images taken earlier in the day.

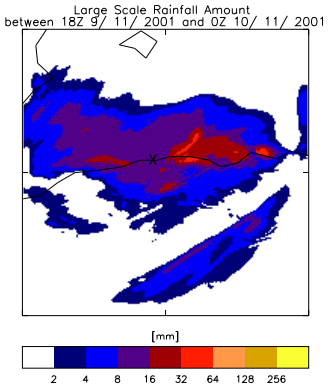
Looking in more detail at the contributions of the large scale and convective scale components to the total precipitation field, Figure 19 shows that it is now the large scale rainfall that contributes the most.

At a horizontal resolution of 4 km, the large scale rainfall is now clearly the more dominant component of the total precipitation field, both in terms of distribution and magnitude. For the eighteen hour duration of the event, the large scale component now has a local maximum of 143 mm which is located just to the east of Algiers, while the convective rainfall has a local maximum of just 22 mm, located in the far west of the model domain. Significantly, this suggests that the principal forcing of the rainfall occurred on a horizontal scale between 4 km and 20 km. As such, it appears that factors pertaining to the large scale flow, rather than the local scale orography played the dominant role in the forcing of the heavy rainfall that fell over Algiers and its surrounding regions. This result is discussed in more detail later on. As before, both the large scale and convective scale rainfall fields suggest that the most intense period of the event has passed by mid-morning on the 10^{th}.

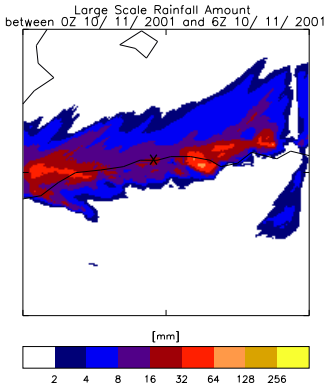
Figure 20 tracks the development of the PMSL field between 0000 UTC and 1200 UTC on the 10^{th} November.

For the same period, Figure 21 shows the evolution of the 500 hPa geopotential height field.

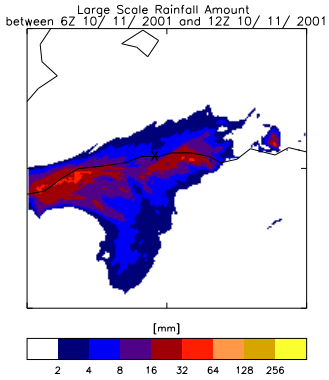
Both the PMSL and 500 hPa geopotential height fields are modelled well by the 4 km model when compared to analyses. There is also a good correspondence with forecasts for the same fields from the 60 km and 20 km models. Figure 20 shows a region of sub 1000 hPa PMSL just to the southeast



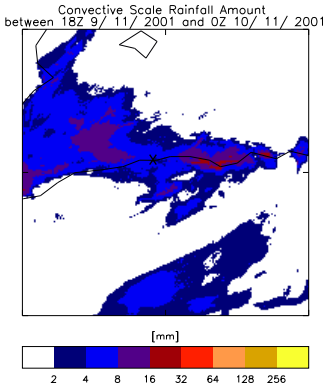
(a) T+9 to T+15 from 0900 UTC on 9/11.



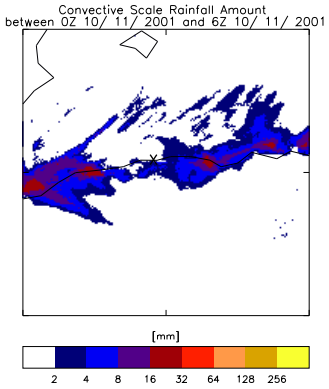
(b) T+15 to T+21 from 0900 UTC on 9/11.



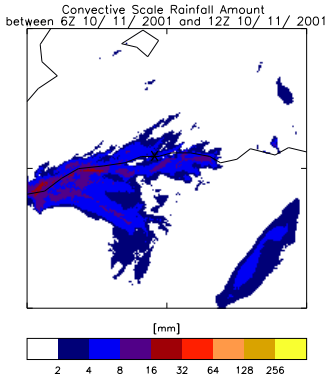
(c) T+21 to T+27 from 0900 UTC on 9/11.



(d) T+9 to T+15 from 0900 UTC on 9/11.

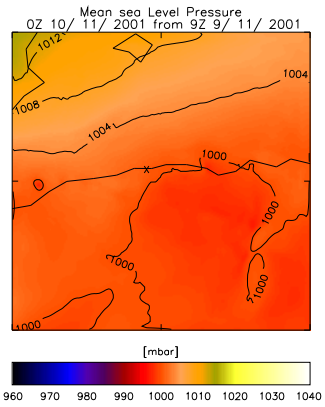


(e) T+15 to T+21 from 0900 UTC on 9/11.

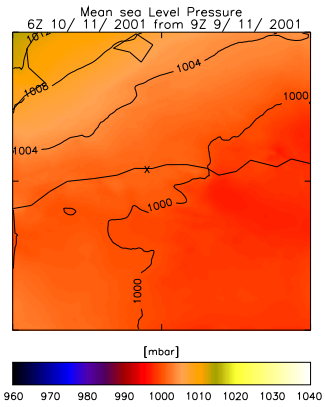


(f) T+21 to T+27 from 0900 UTC on 9/11.

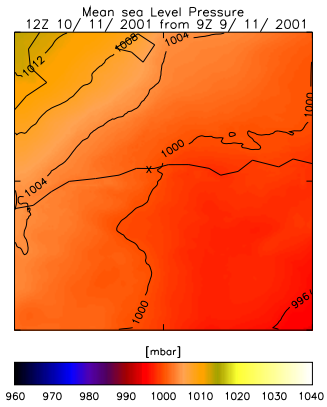
Figure 19: 6-hour accumulations of the large scale and convective scale precipitation fields from a 4 km forecast started at 0900 UTC on the 9^{th} November. Panels a) and b) and c) show the large scale component of rainfall while panels d), e) and f) show accumulations of the convective scale rainfall. Please note the change in scale from previous plots.



(a) T+15 from 0900 UTC on 9/11.

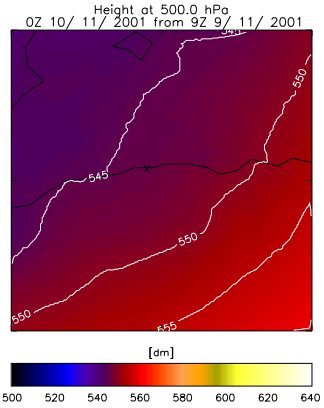


(b) T+21 from 0900 UTC on 9/11.

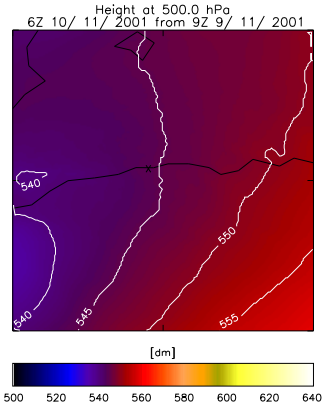


(c) T+27 from 0900 UTC on 9/11.

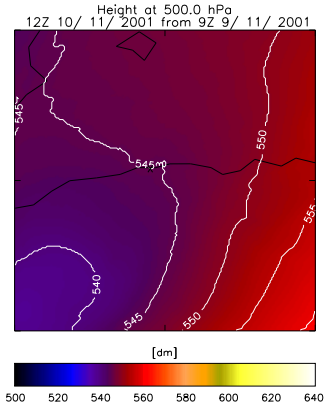
Figure 20: 4km model forecasts of PMSL for a) 0000 UTC on the 10^{th} November, b) 0600 UTC on the 10^{th} November and c) 1200 UTC on the 10^{th} November. The forecast was started at 0900 UTC on the 9^{th} November.



(a) T+15 from 0900 UTC on 9/11.



(b) T+21 from 0900 UTC on 9/11.



(c) T+27 from 0900 UTC on 9/11.

Figure 21: 4km model forecasts of 500 hPa geopotential height for a) 0000 UTC on the 10^{th} November, b) 0600 UTC on the 10^{th} November and c) 1200 UTC on the 10^{th} November. The forecast was started at 0900 UTC on the 9^{th} November.

of Algiers that remains almost stationary for the twelve hour period shown. At both 0600 UTC and 1200 UTC on the 10^{th}, the model is predicting a PMSL minimum of 994 hPa. This is slightly lower than the analysed minimum in Figure 1, although the timings are slightly different.

The 500 hPa geopotential height forecasts show a striking resemblance to the analyses, particularly those from NCEP (Figure 2). With a local minima of just 540 dm and the emerging development of a cut-off low (Figure 21(c)) at 1200 UTC on the 10^{th}, the 4 km model has made a good job of forecasting the general development of the weather system over Algiers for the duration of the event.

Although not shown here, forecasts of other model fields such as the 700 hPa relative humidity also

compare well and highlight more local detail than is possible at coarser resolutions. The relative humidity field in particular forecasts the development of the dry intrusion well compared to both the corresponding 20 km model forecasts and the available satellite imagery.

In the 60 km and 20 km runs, only small differences were observed between forecasts that were set running at different times. This is in part due to the use of data assimilation in these runs. To see the effect that a different start time, i.e. different initial conditions, has on the model forecast, two other forecasts were made with the 4 km model. These forecasts were initiated six hours prior to 0900 UTC on the 9^{th} November at 0300 UTC and six hours later at 1500 UTC on the 9^{th}. Figure 22 compares 6-hour accumulations of the model total precipitation field for the period 1800 UTC on the 9^{th} to 1200 UTC on the 10^{th} for the main 4 km run (hereafter the "control" run) and the two new runs.

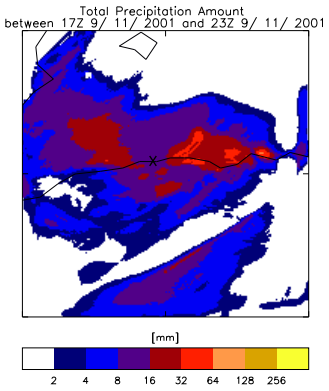
Figure 22 is interesting in that it shows how a difference of just six hours can, when a fine-scale data assimilation scheme is not included, significantly alter the model forecasts. In this case, it is found that both the distribution of the precipitation and the magnitude of the accumulations vary with each forecast. This may be because of the initial adjustment of the model to the interpolated initial conditions from the 20 km analyses. There are also noticeable differences in the timings of the development of the most intense periods of the event. The 1500 UTC forecast (Figures 22(g), 22(h) and 22(i)) seems to completely mistime the most intense period of the event compared to the two earlier forecasts and the analyses. Furthermore, it does not appear to have well forecast the two regions of heavy rainfall, instead concentrating its heaviest rainfall in the west of the model domain. All of the forecasts do, however, broadly agree on there being a band of rainfall that stretches along the Algerian coastline.

Where the model has had the longest spin-up time (Figures 22(d), 22(e) and 22(f)) there is an initially intense period of rainfall to the east of Algiers with a local maximum of 86 mm. This region decreases in size over the next six hours and moves closer to Algiers. For the period 2300 UTC on the 9^{th} to 0500 UTC on the 10^{th}, the local maximum is now just 75 mm and although less than the 93 mm accumulated by the 0900 UTC forecast for the same period, does at least place the maximum in the same location as the 0900 UTC forecast. To the west of Algiers, the 0300 UTC forecast does have a relatively strong region of rainfall but it is located predominately over the sea. The 0900 UTC forecast on the other hand positions the rainfall in the west of the domain much closer to land.

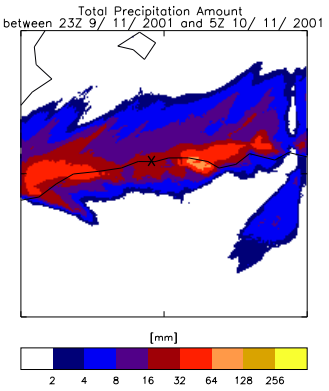
Summing the local maximum accumulations for the period 1700 UTC on the 9^{th} to 1100 UTC on the 10^{th} gives 119 mm for the 0300 UTC forecast, located to the east of Algiers, 157 mm for the 0900 UTC forecast, also located just to the east of Algiers and 142 mm for the 1500 UTC forecast. In this case, the maximum is located in the far west of the model domain.

Thus, we find that the interpolated initial conditions supplied to the model have an effect on timings, location and magnitude of any features that develop during the forecasts. A number of these discrepancies may be better accounted for with the use of additional observations although, with the 1500 UTC forecast especially, the relatively short spin-up time of just three hours before the onset of the event, as recorded by the rain gauge data, is likely to have had a bigger role in determining the model's prediction.

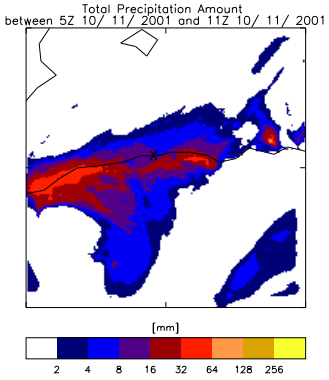
In the following sections, results from numerical experiments where different aspects of the model set up are altered are briefly discussed. These will be discussed primarily in terms of their effects on the total precipitation field.



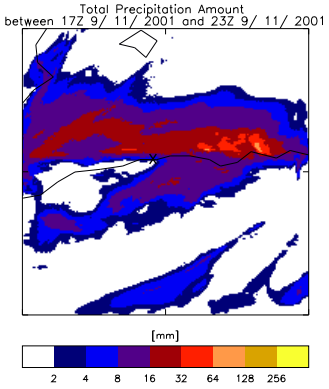
(a) T+8 to T+14 from 0900 UTC on 9/11.



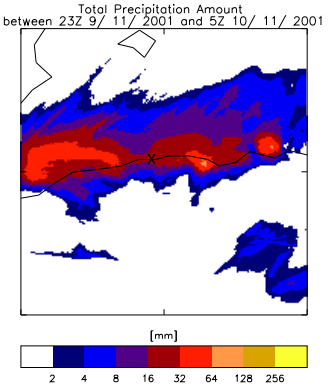
(b) T+14 to T+20 from 0900 UTC on 9/11.



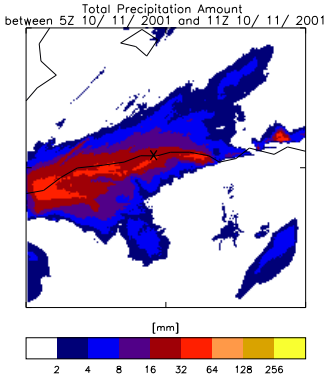
(c) T+20 to T+26 from 0900 UTC on 9/11.



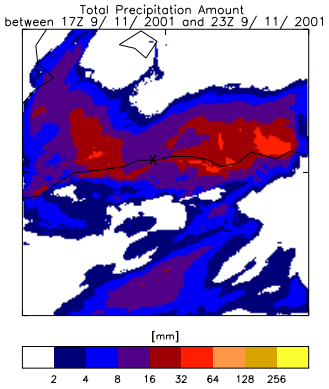
(d) T+14 to T+20 from 0300 UTC on 9/11.



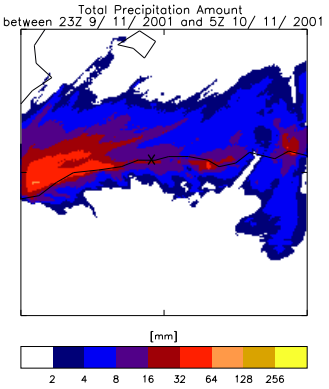
(e) T+20 to T+26 from 0300 UTC on 9/11.



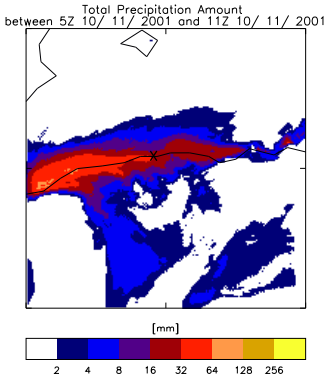
(f) T+26 to T+32 from 0300 UTC on 9/11.



(g) T+2 to T+8 from 1500 UTC on 9/11.



(h) T+8 to T+14 from 1500 UTC on 9/11.

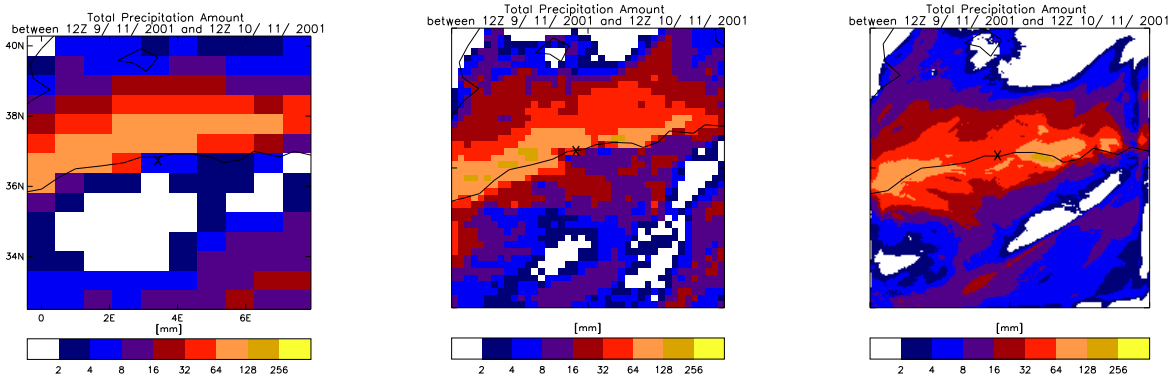


(i) T+14 to T+20 from 1500 UTC on 9/11.

Figure 22: 6-hour accumulations of the total precipitation field from a), b) and c) a 4 km model forecast started at 0900 UTC on Friday 9^{th} November, d), e) and f) a 4 km forecast started at 0300 UTC on the 9^{th} and g), h) and i) a 4 km forecasts started at 1500 UTC on the 9^{th}.

5.3.1 The effect of changing the horizontal resolution

Although all of the results previously described have shown how an increase in horizontal resolution has, for this case, led to improvements in the forecasts of the event, until now a direct comparison has not been made. Figure 23 directly compares the accumulations of total precipitation from the 60 km, 20 km and 4 km models for the 24-hour period 1200 UTC on the 9^{th} to 1200 UTC on the 10^{th} November.



(a) 60 km model. (b) 20 km model. (c) 4 km model.

Figure 23: 24-hour accumulations of the total precipitation amount for the period 1200 UTC on the 9^{th} November to 1200 UTC on the 10^{th} November for a) the 60 km model, b) the 20 km model and c) the 4 km model.

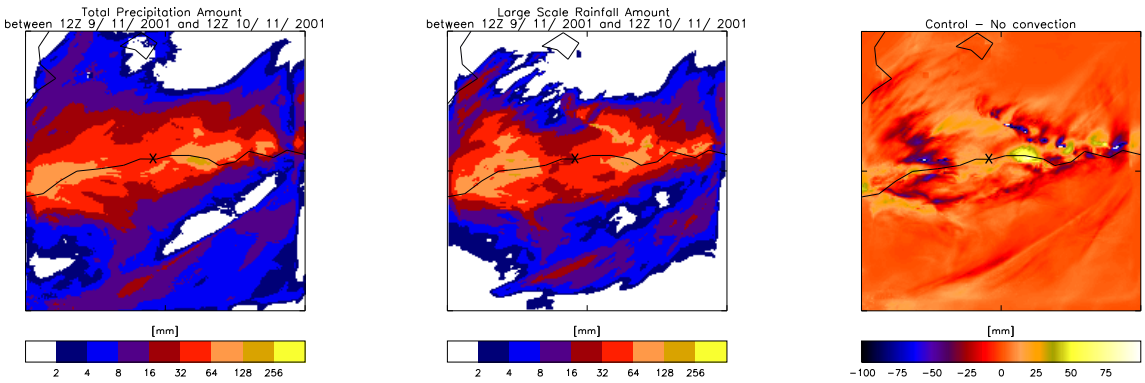
Comparing accumulations from the three different models, but over the same domain size, instantly shows up the differences a change in horizontal resolution can bring about. Most obvious is the increase in local detail as the resolution becomes finer and, for this event, the prediction of two separate regions of high rainfall as opposed to the continuous band seen on the 60 km model. As has been discussed already, however, the increase in resolution has not automatically led to a vast improvement in terms of the location and intensity of the maximum precipitation. In all three cases, the local maximum never reaches 200 mm let alone the 260 mm recorded at Bouzareah during the event.

5.3.2 The role of convection

At a horizontal resolution of 4 km, the model dynamics are on the cusp of being almost able to explicitly resolve convective processes. That is, convective processes can be simulated in the model without the need for a convection parameterisation scheme. In this experiment, the convection scheme in the model is turned off and a T+36 forecast from 0900 UTC on the 9^{th} November is run and compared against the control run. Figure 24 shows how this model change influences the precipitation field.

Note in Figure 24 that the total precipitation amount from the control run has been compared with the large scale rainfall amount in the run without convection. This is because switching off convection means there can be no convective rainfall, leaving only the large scale rainfall.

Switching off convection has had a very large impact on the precipitation field. While the distribution of the precipitation remains similar to the control run, there exist large differences, particularly in



(a) Control run.

(b) Run without convection.

(c) Difference.

Figure 24: Plots showing a) a 24-hour accumulation of the total precipitation amount for the control run, b) a 24-hour accumulation of the large scale rainfall amount for the 4 km run without convection and c) the difference between the two fields. The accumulations are taken over the period 1200 UTC on the 9^{th} to 1200 UTC on the 10^{th} November.

and around the regions of heaviest rainfall. A striking result linked to this observation is the 24-hour local accumulation maximum of 240 mm recorded just to the east of Algiers in the run without convection. The largest of the differences between the two accumulations, up to 100 mm in some places, generally occur along the coastline or over the sea.

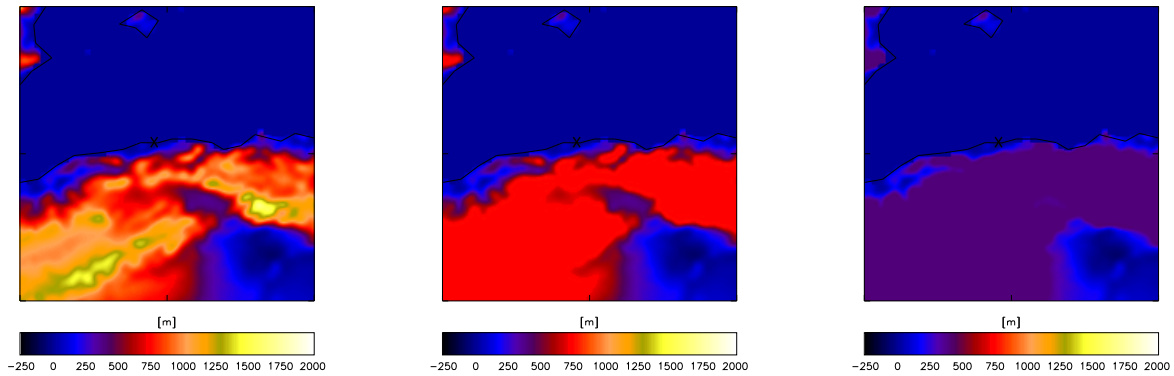
Apart from one or two areas, removing the convection scheme appears to have made the model wetter than the control run. This is likely due to an increase in the amount of CAPE generated by the model as the forecast progresses. With no convection scheme to rain out any excess moisture associated with an increase in CAPE on small scales and help stabilise the model atmosphere, CAPE in the run without a convection is allowed to continue to build up until at some point the large scale dynamics is able to start precipitating out the excess moisture. This may also explain why the biggest differences are near the coast or over the sea. Either way, this result shows how the event was of a highly convective nature and supports the suggestion that it was a MCS that affected the region over Algiers. The region of high rainfall to the west of Algiers exhibits much less of a difference and fits with the suggestion that an occlusion was responsible to the heavy rainfall over this region of Algeria and not the MCS.

5.3.3 The role of orography

Two experiments were conducted which altered the orography of the 4 km model domain. The first imposed a maximum orographic height of 750 m and the second a maximum orographic height of 400 m. The maximum height in the full orographic height field is just over 1.6 km. Figure 25 compares the full, unaltered orography (25(a)) against the two scenarios where the maximum height is 750 m (Figure 25(b)) and 400 m (Figure 25(c)).

For the 24-hour period between 1200 UTC on the 9^{th} to 1200 UTC on the 10^{th} November, Figure 26 compares the total precipitation accumulation from the model run with the unaltered orography (the control run) with the accumulations from the two runs where the domain orography is altered.

Although there is little obvious difference to the distribution of the precipitation, greater, more

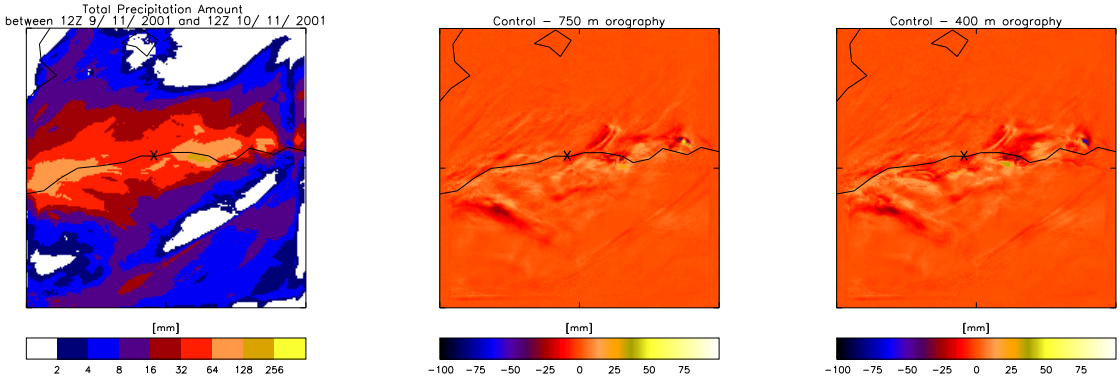


(a) Full orography.

(b) Orography with a 750 m limit.

(c) Orography with a 400 m limit.

Figure 25: Plots showing, for the 4 km model domain, a) the unaltered domain orography, b) the orography when a maximum height of 750 m is imposed and c) the orography when a maximum height of 400 m is imposed.



(a) Control.

(b) Control - 750 m run.

(c) Control - 400 m run.

Figure 26: Plots showing a) the 24-hour accumulation of the total precipitation amount for the period 1200 UTC on the 9^{th} November to 1200 UTC on the 10^{th} November using the 4 km model with the original orography and, for the same 24-hour period, b) the difference between the control run and the run where the maximum orographic height is 750 m and c) the difference between the control run and the run where the maximum orographic height is 400 m.

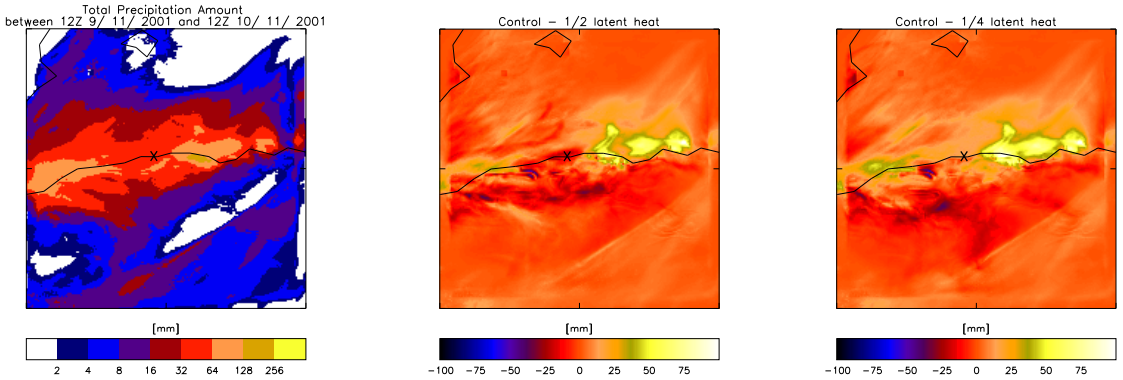
localised precipitation is forecast when the maximum orographic height is reduced. This is evident in the coastal region to the east of Algiers where the precipitation totals for the 24-hour period increase from 166 mm using the unaltered orography to 177 mm where a maximum orographic height of 750 m is imposed and 187 mm when the maximum height is 400 m. There is a second region of increased precipitation when the maximum orographic height is reduced further inland and to the southwest of Algiers. Here, an increase in total precipitation of up to 30 mm on the control run is found and appears related to the removal of a 1300 m peak that is present in the full orography field.

With the majority of the peaks removed from the local orography, the increase in precipitation is

less likely due to orographic enhancement but rather the large scale flow adjusting to the revised orography. In effect, the role of the orography as a blocking feature has been reduced. Indeed, compared to the control run, the relative humidity at lower levels reveals larger regions of moist air moving inland as the maximum orographic height is reduced. Examining the relative humidity at 950 hPa (not shown) reveals that those regions where the most height has been removed from the orography have become more saturated compared to the corresponding relative humidity field in the control run. In places, the air is up to 40% more saturated. This result also lends support to the suggestion of Tripoli *et al.* (2002) that the precipitation event itself was not overly enhanced by the local orography.

5.3.4 The role of latent heat

The studies of Genovés and Jansà (2002) and Hamadache *et al.* (2002) discussed the role of the latent and sensible heat fluxes in the generation and subsequent development of the cyclone that was located over Algiers. To investigate this further, two runs of the 4 km model were made with the values of the latent heat of condensation at 0°C (L_c) and latent heat of fusion at 0°C (L_f) reduced firstly by half and secondly by a factor of four. The first run used $L_c = 1.251\times10^6$ Jkg^{-1} and $L_f = 0.167\times10^6$ Jkg^{-1}, while the second run reduced these values further to, $L_c = 0.626\times10^6$ Jkg^{-1} and $L_f = 0.084\times10^6$ Jkg^{-1}. The control run used $L_c = 2.502\times10^6$ Jkg^{-1} and $L_f = 0.334\times10^6$ Jkg^{-1}. Figure 27 shows the differences in the total precipitation fields from the three runs for the 24-hour period 12 UTC on the 9^{th} to 12 UTC on the 10^{th} November.



(a) Control.

(b) Control - 1/2 latent heat.

(c) Control - 1/4 latent heat.

Figure 27: Plots showing a) the 24-hour accumulation of the total precipitation amount for the period 12 UTC on 9^{th} November to 12 UTC on 10^{th} November using the 4 km model where L_c and L_f have their original values and, for the same 24-hour period, b) the difference in total precipitation amount between the control run and the run where L_c and L_f are halved and c) the difference in total precipitation amount between the control run and the run where L_c and L_f are reduced by a factor of four.

Compared to the change in precipitation fields that resulted from changes to the domain orography, reducing the effect of latent heating has had a much larger effect on the total precipitation amounts, both in terms of precipitation amount and distribution. In general, reducing the role of latent heating has led to a decrease in precipitation, particularly in the regions of most intense rainfall along the coast to the east of Algiers. Looking at the effects on the large scale and convective scale rainfall

separately showed the convective scale rainfall to be most affected by the reduction in latent heating.

Compared to the control run maximum accumulation of 166 mm, halving the contribution of latent heating (Figure 27(b)) has resulted in a maximum accumulation of just 130 mm. This is less than the maximum accumulation for the same period forecast by the 20 km model. There are, however, a number of small areas, particularly to the south and south west of Algiers where the precipitation amount has increased compared to the control run.

When L_c and L_f are reduced by a factor of four (Figure 27(c)), the differences that were seen when L_c and L_f were halved simply become more exaggerated and the maximum precipitation accumulation is now only 125 mm. The region to the east of Algiers in particular, is now indicating differences of up to 75 mm less precipitation than is found in the control run for the same 24-hour period. While, like in Figure 27(b), local increases in precipitation, compared to the control run, are found to the south and southwest of Algiers, there is also a large region of less intense precipitation along the coast to the west of Algiers. Here, reducing the effect of latent heating has led to a 40 mm reduction in the amount of precipitation forecast by the model compared to the control run.

In summary, the 4 km model, while not improving on the performance in terms of the maximum precipitation accumulation, has highlighted the improvement in local details that using such a high resolution brings. It has also been shown that the principal forcing behind the severe precipitation event was latent heating and not orographic forcing which instead was found only to influence the distribution of the precipitation.

In the next section, the results of the numerical simulations are discussed along with their implications for understanding the severe precipitation event of the 9^{th} and 10^{th} November 2001.

6 Discussion

The numerical simulations presented in this study have shown the severe precipitation event of the 9^{th} and 10^{th} November to be well forecast at global (60 km), regional (20 km) and national (4 km) scales. The 60 km and 20 km models forecast a sufficient amount of rainfall near to Algiers that would have alerted the forecaster to a period of severe weather. Whilst not quite getting the location or maximum intensity right, compared to analyses, these models did get the timing and duration of the event right. Both predicted the heaviest rainfall would fall in the first six hours of the morning of the 10^{th} November. Forecasts of the other large scale meteorological fields such as PMSL, geopotential height and relative humidity were considered to be well forecast when compared against analyses and available satellite imagery.

The 4 km model, while not improving on the performance of the 60 km and 20 km models in terms of the maximum precipitation accumulation, highlighted the improvement in local details that using such a high resolution brings. However, the inability of the model to correctly position the regions of heaviest rainfall suggests that use of a high resolution model alone can not guarantee a good forecast. Coupled with this is the important result that the forecasts were shown to be sensitive to the initial conditions. This suggests that, where possible, a numerical model forecast should be supplemented with observations from both ground-based instruments and satellites. This could be in the form of a visual aid to the forecaster or as input for a fine-scale data assimilation scheme for the model. For a fine-scale data assimilation scheme to be useful, however, any observations included would need to be of a spatial and temporal resolution high enough to influence both the dynamical and thermodynamical structure of the boundary layer and the lower- and mid-troposphere.

Numerical experiments carried out using the 4 km model have shown that the severe precipitation over Algiers was the result of a highly convective system. The results presented in this report suggest the extreme precipitation that fell over Bouzareah was the result of a MCS. The heavy rain that fell to the west of Algiers over Arzew and Oran appears to be most likely due to an occlusion. These two systems were not related and were separated by a dry intrusion that was not only observed in satellite imagery and hinted at in the rain gauge data but forecast well by the numerical models at all three resolutions. It has also been shown that the main forcing was on a horizontal scale somewhere between 4 km and 20 km. A model run with a horizontal resolution of 12 km may help narrow this range further.

Experiments looking into the respective roles of the local orography and latent heating showed the principal forcing mechanism to be the latent heating of the atmosphere. Removal of heat from the atmosphere made the region severely less convective and a large reduction in the amount of precipitation resulted. In contrast, removing the major peaks from the local orography had a greater influence on the distribution of the precipitation rather than the amount. Only in very localised regions, that were found to be coincident with the location of orographic peaks that had been removed, were increases in precipitation found. In these cases, this was attributed to an increase in the amount of moist air that had reached these regions, suggesting the orography played more of a blocking role to low level moisture rather than act to enhance the precipitation.

The good agreement, where comparisons could be made, of the model forecasts with available analyses suggests that the modelling techniques and indeed the model set up used in this study was appropriate for investigating an event of the nature experienced over Algiers in November 2001. However, there is a clear need, particularly evident in the high resolution runs, for the use of supporting observations. Further improvements to the model forecasts of this and similar events could also be brought about through improvements to the model physics schemes and adjustments to the model timings (e.g. the model time step). To assess this, studies of many more events would be needed.

A How the Met Office responded to the event

Shown here are a collection of messages and announcements that detail how the Met Office and other parties identified, tracked and responded to the severe precipitation event.

Met Office press release issued 9^{th} November 2001:

> British sunseekers face Balearic deluge
>
> 9 November 2001
>
> British holidaymakers escaping this week's cold snap at home face some very wet and windy weather in parts of the Mediterranean over the next few days.
>
> The Balearic Islands, in particular, will be badly affected by a deep depression in the western Mediterranean. This will bring severe weather with several inches of rain and winds in excess of 50 miles per hour.
>
> Chris Jones, Deputy Head of Forecasting at the Met Office, said: "Many people will have been tempted by a sunshine break after this week's wintry weather at home. However, they may need to pack their wellingtons rather than their swimsuits."

This press release came about as a result of the following e-mail conversation involving Julian Heming, the Met Office's Tropical Prediction Scientist. Note from the dates that the system was identified on the 7th November, up to two days ahead of the actual event.

> From: Mark Lander
> Sent: Wednesday, November 07, 2001 3:46 AM
> Subject: [Tropical-storms] Spain-cane?
>
> TC group,
>
> Chris Velden recently alerted me to the forecast development in NOGAPS of a very intense low in the Mediterranean – a possible rare case of a MED-cane? In the meantime, in a search of this part of the world, I came up with a small shear type TC sitting off the SW coast of Spain, a Spain-cane, if you will.
>
> This little TC formed in a manner similar to the several recent TCs in the subtropical Atlantic: An upper low creates a curved band of cbs that undergoes a sort of occlusion process, and then the vortex that breaks away from the primary comma-shaped cloud band goes off on its own and develops persistent central convection and intensifies. Dvorak estimates would yield a T2 or T2.5, or 30-35 kts.
>
> Regards, Mark Lander

In reply, Julian Heming wrote:

> Mark,
>
> The last case of a Mediterranean 'TC' in 1995 had a very small vortex which was barely analysed by global models. Latest forecasts for this one show a low enveloping most of the western Mediterranean (see Figure 28), so it is likely to be a very different sort of system. First visible imagery today shows only limited deep convection around the 'Spain-cane'.
>
> Regards, Julian

A reply from Chris Velden took the form,

Hi Julian.

Boy it sure looks like it begins to take on sub-synoptic scale structure around 3 days out, especially in the NOGAPS. I agree the parent low starts big, but the rapid development west of Italy over the Med sure looks like marine feedback processes may be kicking in.

Chris

A more detailed description of the "TC" (Tropical Cyclone) is now offered.

From: Chris Velden
Sent: Thursday, November 08, 2001 6:35 PM
Subject: Re: Med-cane

This sure looks like a hurricane to me, at least within a global model. Julian, is the UKMET looking like this?

Chris

Julian Heming offered the following reply,

From: Julian Heming
RE: Med-cane
Date: Fri, 09 Nov 2001 10:12:53 +0000

Chris,

This is a very interesting development. NOGAPS has consistently had a more symmetric appearance and deeper central pressure in its forecasts. The Met Office model forecast has a much more elongated shape to the low with a very tight gradient on the north-western flank. I've just been discussing the system with our duty forecasters for the day and they are expecting a potent mix of dynamic and convective forcing in the Balearics over the next few days which will lead to severe conditions. There is already a strong Mistral developing and the associated cold plunge from the north-east is going to encounter warm advection from the Sahara. The model is consequently predicting a strong thermal gradient across the Med and this is being shown on forecaster-produced charts as a frontal zone wrapping round the north and west of the low (chart attached - 72 hour forecast valid 12Z 11th (Figure 28)). Hence, our forecasts are not going for anything which you could say resembles a hurricane or the mesoscale vortex from 1995 mentioned previously. However, our forecasters' latest predictions are for a 50 knot north-easterly and 10-12 inches of rain in the Balearics on Sunday. This is a popular holiday destination for the British this time of year to escape the beginnings of the British winter, so there are probably going to be a lot of disgruntled holiday makers around!

Cheers, Julian

It is seen from this correspondence that the event was recognised early and the Met Office forecasters, using data from the global model, confidently predicted heavy rainfall and disruption in the Balearics (and Algeria) as a result.

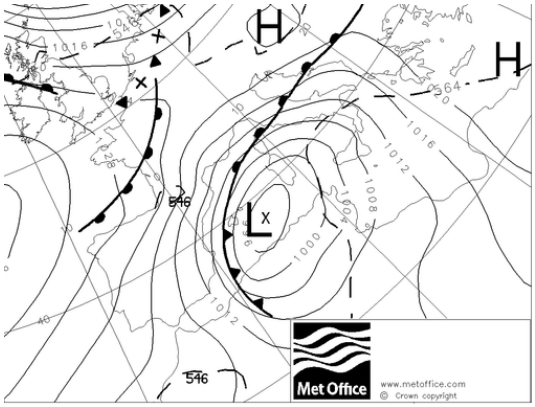


Figure 28: UK Met Office T+72 global model forecast of the Algerian cyclone system on 11^{th} November 2001.

B Project Details

This report was originally prepared for the World Bank funded "*Urban Natural Hazard Vulnerability Reduction Project: Alger Wilaya*" project. The work was carried out by the Met Office on behalf of the Office National de la Météorologie, Algeria.

High Resolution Modelling of the Extreme Precipitation Event over Algiers in November 2001

Scientific report for LOT 2 of the ***Urban Natural Hazard Vulnerability Reduction Project: Alger Wilaya***

Stuart Moore[1], Stuart Bell[1], Clive Wilson[1], Bachir Hamadache[2], Kamel Chikhar[2]

[1] *Met Office, FitzRoy Road, Exeter, EX1 3PB, UK*
[2] *Office National de la Météorologie, BP 153, Avenue Khemisti, DEB 116011, Alger, Algeria*

Budget Equipment
Opération No. ND.5.552.2.262.010.23
Développement des capacitiés de gestion des catastrophes naturelles
Project financed by the World Bank: R.V.Z.U - PRET No. 7139

References

Arreola, J. L., Homar, V., Romero, R., and Ramis, C. Alonso, S. (2002). Multiscale Numerical Study of the 10-12 November 2001 Strong Cyclogenesis Event in the Western Mediterranean. In *Mediterranean Storms: Proceedings of the 4^{th} EGS Plinius Conference.*

Clark, P., Lean, H., Roberts, N., and Forbes, R. (2004). Mesoscale NWP Performance - 16^{th} August 2004. Unpublished JCMM report.

Cullen, M. J. P. (1993). The unified forecast/climate model. *The Meteorological Magazine*, pages 81–94.

Davies, T., Cullen, M. J. P., Malcolm, A. J., Mawson, M. H., Staniforth, A., White, A. A., and Wood, N. (2004). A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Q.J.R. Meteorol. Soc.* Accepted for publication.

Deshons, P. and Delrieu, G. (2002). Urban Flood Management in Marseille (France): the case study of 19 September 1999. In *MITCH Workshop II: Advances in flood forecasting, flood warninng and emergency mamagement, Barcelona, 10-12 June 2002.*

Edwards, J. M. and Slingo, A. (1996). Studies with a flexible new radiation code. Part I: Choosing a configuration for a large-scale model. *Q.J.R. Meteorol. Soc.*, **122**, 689–719.

Faccani, C., Ferretti, R., and Visconti, G. (2003). High-Resolution Weather Forecasting over Complex Orography: Sensitivity to the Assimilation of Conventional Data. *Monthly Weather Review*, **131**, 136–154.

Ferraris, L., Rudari, R., and Siccardi, F. (2002). The Uncertainty in the Prediction of Flash Floods in the Northern Mediterranean Environment. *Journal of Hydrometeorology*, **3**, 714–727.

Fierli, F., Pinori, S., Dietrich, S., Medaglia, C., and Tripoli, G. J. (2002). Potential Vorticity Analysis of the Storm Event of the 9-10 November Algerian Flood. In *Mediterranean Storms: Proceedings of the 4^{th} EGS Plinius Conference.*

Genovés, A. and Jansà, A. (2002). Diabatic Processes Contribution to the November 2001 Storm. In *Mediterranean Storms: Proceedings of the 4^{th} EGS Plinius Conference.*

Gregory, D. and Rowntree, P. R. (1990). A mass flux scheme with representation of cloud ensemble characteristics and stability dependent closure. *Monthly Weather Review*, **118**, 1483–1506.

Hamadache, B., Terchi, A., and Brachemi, O. (2002). Study of the meteorological situation which affected the west and the center of Algeria in general and Bab-el-Oued in particular in the 10^{th} November 2001. In *Mediterranean Storms: Proceedings of the 4^{th} EGS Plinius Conference.*

Hastings, D. A., Dunbar, P. K., Elphingstone, G. M., Bootz, M., Murakami, H., Maruyama, H., Masaharu, H., Holland, P., Payne, J., Bryant, N. A., Logan, T. L., Muller, J.-P., Schreier, G., and MacDonald, J. S., e. (1999). The Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model, Version 1.0. Technical report, National Oceanic and Atmospheric Administration, National Geophysical Data Center, 325 Broadway, Boulder, Colorado 80303, U.S.A. Digital data base on the World Wide Web (URL: http://www.ngdc.noaa.gov/seg/topo/globe.shtml) and CD-ROMs.

Lean, H. W. (2003). High Resolution Trial Model Project (HRTM). Technical report, Met Office, Joint Centre for Mesoscale Meteorology, The University of Reading. End Project Report.

Lock, A. P., Brown, A. R., Bush, M. R., Martin, G. M., and Smith, R. N. B. (2000). A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. *Monthly Weather Review*, **128**, 3187–3199.

Lorenc, A. C., Ballard, S. P., Bell, R. S., Ingleby, N. B., Andrews, P. L. F., Barker, D. M., Bray, J. R., Clayton, A. M., Dalby, T., Li, D., Payne, T. J., and Saunders, F. W. (2000). The Met. Office Global 3-Dimensional Variational Data Assimilation Scheme. *Q. J. R. Meteorol. Soc.*, **126**, 2991–3012.

Martin, G. M., Bush, M. R., Brown, A. R., Lock, A. P., and Smith, R. N. B. (2000). A new boundary layer mixing scheme. Part II: Tests in climate and mesoscale models. *Monthly Weather Review*, **128**, 3200–3217.

Moore, J. T. (2003). Mesoscale Convective Systems. Lecture notes for Comet Hydrometeorology course, 14-21 August 2003, Web page: http://www.eas.slu.edu/CIPS/Presentations/Hydromet2003/MCSs/index.htm, last accessed 05/11/2004.

Pinori, S., Adamo, C., Di Michele, S., Mugnai, A., Tassa, A., Tripoli, G. J., and Smith, E. A. (2002). Satellite Observations of Heavy Rain Producing Storms over the Mediterranean Area. In *Mediterranean Storms: Proceedings of the 4^{th} EGS Plinius Conference.*

Riosalido, R., Carretero, O., Elizaga, F., and Martin, F. (1998). An Experimental Tool for Mesoscale Convective Systems Nowcasting. In *Proceedings of SAF Training Workshop: Nowcasting and Very Short Range Forecasting, 9-11 December 1998, Madrid, Spain.*

Roberts, N. (2003). Results from high resolution modelling of convective events (Stage 1 report from the Storm-Scale numerical modelling project). Technical Report Forecasting Research Technical Report No. 402, Met Office, Joint Centre for Mesoscale Meteorology, The University of Reading. Joint Centre for Mesoscale Meteorology Report No. 140.

Tripoli, G. J., Pinori, S., Dietrich, S., Panegrossi, G., Mugnai, A., and Smith, E. (2002). The 9-10 November, 2001 Algerian Flood: A Polar Low? In *Mediterranean Storms: Proceedings of the 4^{th} EGS Plinius Conference.*

Webster, S., Brown, A. R., Cameron, D. R., and Jones, C. P. (2003). Improvements to the representation of orography in the Met Office Unified Model. *Q. J. R. Meteorol. Soc.*, **129**, 1989–2010.

Wilson, D. R. and Ballard, S. P. (1999). A microphysically based precipitation scheme for the UK Meteorological Office Unified Model. *Q.J.R. Meteorol. Soc.*, **125**, 1607–1636.

Zipser, E. J. (1982). Use of a conceptual model of the life-cycle of mesoscale convective systems to improve very-short-range forecasts. In K. A. Browning, editor, *Nowcasting*, pages 191–204. Academic Press, London.